DEVELOPMENT OF A SCALE OF OPTICAL RADIATION

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Summary

A description is given of the development *ab initio* of a scale of optical radiation, in terms of which sources can be calibrated for radiant intensity and detectors for radiant sensitivity. The scale is considered to be accurate to within about $\pm 0 \cdot 2\%$.

I. Introduction

The measurement of the power in a beam of optical radiation continues to be a difficult undertaking, a great deal of experience and effort being required to achieve an accuracy of 1% or better. Most measurements of this type use radiation standards developed either by national standardizing laboratories or by meteorological institutions.

Some of the national laboratories have based their standards on the radiant intensity of a black-body source at a known temperature as given by the Stefan–Boltzmann law, while others have used as their starting point thermal detectors of radiation that can be calibrated in terms of well-founded physical quantities. For example, the U.S. National Bureau of Standards has used a black-body source at temperatures between 1300 and 1400°K (Stair, Schneider, and Fussell 1967) and the Canadian National Research Council has used one between 310 and 420°K (Bedford 1960). On the other hand, the British National Physical Laboratory (Gillham 1962) and the Japanese Electrotechnical Laboratory (Ooba 1965) have used thermal detectors in which electrical heating is substituted for radiant heating, and they have thus measured radiant power in terms of the electrical watt. The first thorough intercomparison of the national radiation scales has recently been conducted by the National Physical Laboratory on behalf of the Comité International des Poids et Mesures (C.I.P.M.), and a preliminary report shows a spread of over 2% between the eight participating laboratories (Bureau International des Poids et Mesures, personal communication).

Most radiation measurements in meteorology are based not on the work of the standardizing laboratories but on scales developed from direct measurements of solar radiation with absolute thermal detectors. For many years two such scales were used, even though they were known to differ by about $3 \cdot 5\%$, but in 1956 a single compromise scale called the 1956 International Pyrheliometric Scale was adopted (IGY 1958). Few attempts have been to made compare the meteorological and the national scales but the little evidence available suggests that they agree to within a few per cent.

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In Australia, as elsewhere, meteorological measurements of radiation are mostly based on the International Pyrheliometric Scale, the maintenance of the scale and the calibration of instruments in terms of it being carried out by the Division of Meteorological Physics, CSIRO. Hitherto the National Standards Laboratory has used as radiation standards a group of filament lamps calibrated at the National Bureau of Standards, but in view of an international move towards improving the accuracy of radiometry and ultimately redefining the unit of light in radiometric terms (C.I.P.M. 1962), a new radiation scale has recently been established *ab initio*.

II. Basis of the New Scale

The new scale is based on the type of absolute detector in which a blackened receiver is heated alternately by absorption of the radiation to be measured and by a built-in electrical element, the electrical power being adjusted until no variation in the receiver temperature is observable on changing from one form of heating to the other. The irradiance E at the limiting aperture of the detector is then given by

$$E = P/A\alpha,$$

where P is the electrical power input at balance, A the area of the limiting aperture, and α the absorptance of the receiver.

A most desirable feature of this method is that the only existing standards of measurement invoked, namely those of electrical power and of area or length, are more accurate than existing radiation standards by some orders of magnitude. This advantage is not achieved if a black-body source is used as a radiation standard. When applying the Stefan–Boltzmann law, which relates the flux Φ emitted per unit area and the source temperature T by the equation

$$\Phi = \sigma T^4,$$

selection of the best value for the Stefan–Boltzmann constant σ presents an immediate problem, as theoretical and experimental evaluations of σ are in poor agreement. Theoretical evaluation is based on the relationship between σ and three more fundamental constants, namely Boltzmann's constant k, Planck's constant h, and the velocity of light c, and gives a value of $5\cdot670\pm0\cdot001$ pW cm^{-2} degK^{-4} (Cohen and DuMond 1965). However, experimental determinations of σ have consistently given a higher value (Stair, Schneider, and Fussell 1967), the results of eight independent determinations lying within the range $5\cdot72$–$5\cdot80$ and having a mean of $5\cdot76$ pW cm^{-2} degK^{-4}, which is $1\cdot6$% greater than the theoretical value. Errors in measuring thermodynamic temperatures are also likely to increase significantly the uncertainty in applying the Stefan–Boltzmann law, especially when the temperature is high. For example, recent measurements of the freezing point of gold have varied over the range $1336\cdot8$–$1337\cdot6$°K; moreover, a recent international comparison of the temperature scales of six laboratories has shown differences ranging from $3\cdot5$ degK at the gold-point to $5\cdot5$ degK at about 2200°K (C.I.P.M. 1964). Operation at lower temperatures would greatly reduce the uncertainty arising from errors in temperature measurement, but the consequent concentration of the radiation at longer wavelengths would be undesirable for many purposes and for photometric applications in particular.

III. The Radiation Field

It was decided to construct the absolute radiometers specifically for measuring irradiance, and the provision of a uniform and reproducible field of radiation was therefore necessary. Figure 1 shows the arrangement used. The source was a 30 V, 6 A type Wi 41/G gas-filled incandescent lamp made by Osram G.m.b.H. of Germany, having a uniplanar straight tungsten filament and a conical glass envelope blackened

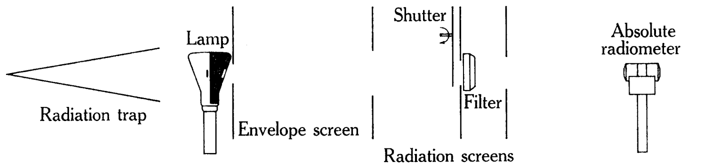

Fig. 1.—Experimental arrangement for absolute measurements of irradiance.

on the forward half except for a $2 \cdot 5$ cm square window in front of the filament. The lamp was operated cap downwards at the colour temperature 2854°K, and the irradiance measurements were of the plane parallel to and distant 1 m from the filament plane, at the point where the plane intersects the normal through the centre of the filament.

About 25% of the lamp radiation in the direction of measurement was found to have been emitted by the envelope, this being about twice as much as with similar lamps having clear envelopes. It was advantageous to filter out this long wavelength component as its intensity was likely to vary considerably with ambient temperature and draught conditions and with changes in the atmospheric concentration of water

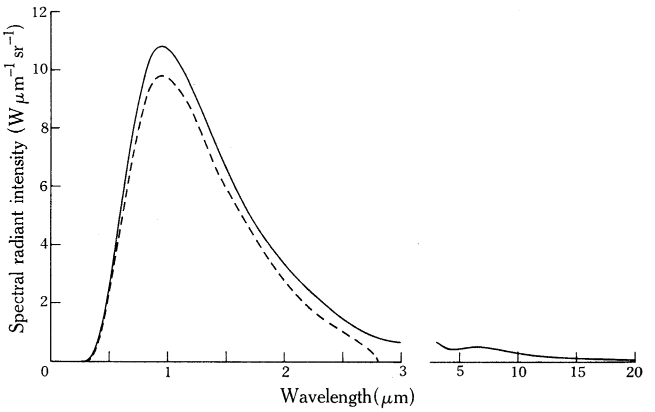

Fig. 2.—Curves of spectral radiant intensity for the lamp used as radiation source without a filter (full curve) and with a 14 mm thick filter of hard crown glass (dashed curve).

vapour. Experiments with different filters showed that the envelope contribution was reduced to 1% by a 3 mm thick plate of glass having a transmittance of about $0 \cdot 9$ over the wavelength range $0 \cdot 4$–$2 \cdot 7$ μm and $0 \cdot 2$ over $2 \cdot 7$–$4 \cdot 0$ μm; was reduced to $0 \cdot 2$% by a 14 mm plate of hard crown optical glass that was opaque beyond $2 \cdot 8$ μm; and was reduced to a negligible fraction by a 1 cm cell of water that was opaque beyond 1·4 μm. As the water filter was inconvenient and also absorbed a substantial fraction of the filament radiation, the 14 mm glass plate was used in conjunction with an opaque metal screen mounted immediately in front of the lamp and provided with a 5 cm square aperture that passed the filament radiation without irradiation of the aperture edges. Figure 2 shows the approximate spectral distribution of the radiant intensity of the lamp, both with and without the filter.

In order to avoid inter-reflection problems the filter was used at an angle of incidence of 20°. Rotating the filter about the optical axis was observed to cause transmittance changes of approximately 0·5%, owing to considerable polarization of the radiation from the lamp, and the filter was therefore used always in a vertical plane to ensure reproducibility of transmittance.

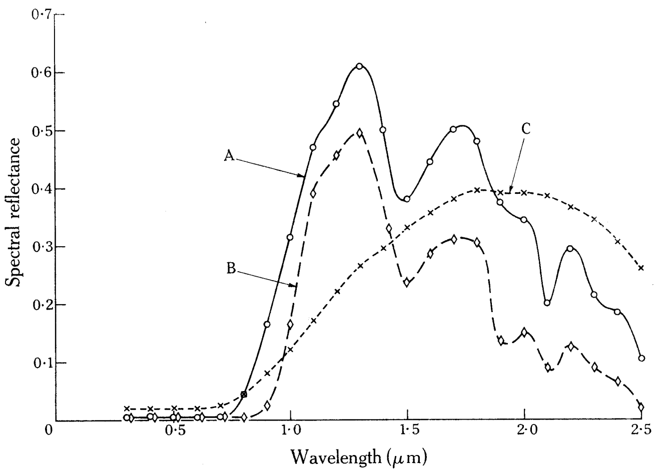

Fig. 3.—Curves of spectral reflectance for two black velvet cloths (curves A and B) from different sources and one black Italian cloth (curve C).

Initially the traditional photometric procedure of using a black cloth as a background to the lamp was adopted, but tests showed that reflection by the cloth increased the irradiance perceptibly, two black velvet cloths of different origin each giving a slightly greater effect than a black Italian cloth. Measurements of spectral reflectance over the wavelength range 0·3–2·5 μm (Fig. 3) showed that all three cloths had high reflectances in the near infrared region. Black cloths were therefore abandoned in favour of a radiation trap in the form of a conical cavity of semi-angle 10°, coated internally with a glossy black paint whose diffuse reflectance was low over the spectral range of interest.

Screens with circular apertures were used as shown in Figure 1 to limit the radiation beam and the angle-of-view of the radiometer. A shutter was opened or closed at 2 min intervals by a synchronous motor, and the electrical heating of the radiometer receiver was switched on automatically as the shutter closed. As the glass filter was opaque to room temperature radiation and was situated on the detector side of the shutter, temperature control of the shutter was not required.

Although the glass filter transmitted negligible radiation beyond 2·8 μm, the irradiance at 1 m from the lamp was found to vary significantly with changes in the water vapour pressure of the atmosphere. Howard, Burch, and Williams (1956) have shown that in the case of weak absorption by water vapour, as with the present short optical path, the absorptance is proportional to the square root of the vapour pressure. Calculations using empirical expressions given by Howard, Burch, and Williams for the various absorption bands of water vapour show that with the spectral energy distribution of our filtered lamp radiation (Fig. 2, dashed curve) the total absorptance α_p of a 1 m path can be expressed as

$$\alpha_p = 0 \cdot 004\,\rho^{\frac{1}{2}},$$

where ρ is the vapour pressure expressed in torr. The absorption is chiefly within the $1 \cdot 4$, $1 \cdot 9$, and $2 \cdot 7$ μm bands, the $0 \cdot 9$ and $1 \cdot 1$ μm bands playing a minor role.

The values of ρ in the laboratory were observed to vary during a year from about 5 to 15 torr, corresponding to a range of values for α_p from $0 \cdot 009$ to $0 \cdot 015$. The above relationship between α_p and ρ was confirmed experimentally by first measuring the irradiance and the prevailing water vapour pressure, and then the increase in irradiance when the optical path was flushed with dry nitrogen. A similar measurement using the 3 mm glass filter in the path instead of the 14 mm one showed that this increased the absorptance α_p by a factor of about $1 \cdot 5$.

IV. The Absolute Radiometers

Two different types of absolute radiometers were constructed, namely thermopiles and bolometers. Both were based on the substitution of electrical for radiant heating but in many other respects they were purposely made to differ widely, the view being taken that close agreement between them would then lead to increased confidence in the radiation scale.

(a) *Absolute Thermopiles*

The first type of radiometer was an absolute thermopile, which, except for the method of blackening the radiation receiver, was largely a copy of Gillham's (1962) disk radiometer. With this instrument (Fig. 4) the inner entrance aperture, which is precisely circular and has a diameter of about 6 mm that is accurately known, is placed in the plane whose irradiance is to be measured. Radiation passing through the aperture irradiates a circular area of the blackened receiver, temperature changes in which are sensed at the back by 28 copper–constantan thermocouples connected in series. The receiver has as base a circular aluminium disk 1 cm in diameter and $0 \cdot 5$ mm thick, with a 50 μm thick mica insulating disk glued to its front surface by shellac. As the sensitivity over the front surface is uniform to better than 1%, the area heated electrically does not have to correspond exactly to that irradiated, and a zigzag element of gold evaporated on the mica before application of the black is satisfactory (Fig. 4(*b*)).

The black coating of the receiver is the most critical part of the thermopile, and a detailed account of the properties of several coating materials has been published elsewhere (Blevin and Brown 1966). That found most satisfactory and used on the present radiometers was a special form of gold-black applied with a thickness of less than 1 μm and electrically insulated from the underlying electrical heating element by a thin layer of lacquer. This coating has the advantages of a high absorptance of about 0·995 for the radiation to be measured, and a low thermal resistance of less than 1·0 degC W^{-1} cm^2 between its front and back surfaces. The latter characteristic is required to avoid serious underevaluation of the radiation, which is absorbed for the most part towards the front of the coating while the electrical element lies at the back, closer to the thermocouples.

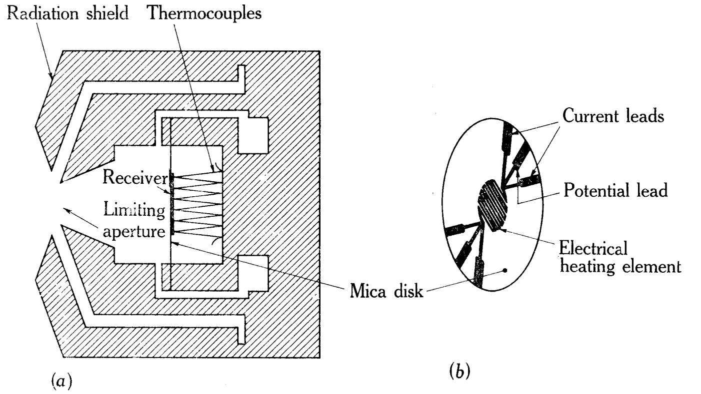

Fig. 4.—Schematic diagram of a Gillham-type absolute thermopile showing (*a*) the complete instrument in section and (*b*) the electrical heating element of evaporated gold on mica. Assembly details are similar to those described by Gillham (1962).

Four absolute thermopiles were constructed and were operated in pairs mounted back-to-back, changes in atmospheric pressure and ambient temperature being largely compensated for by the well-known technique of connecting the back and the irradiated thermopiles in series with opposing polarity. The approximate characteristics of each thermopile were as follows.

Area of limiting aperture	0·28 cm^2
Resistance of heating element	400 Ω
Resistance of each evaporated current lead to heating element	2 Ω
Resistance of thermopile	25 Ω
Time constant	15 sec
Sensitivity	15 mV W^{-1} cm^2
Minimum irradiance detectable	0·5 μW cm^{-2}

The detectivity limit was set by the residual effects of variations in the atmospheric pressure; the quoted value of 0·5 μW cm^{-2} was commonly observed and occasionally bettered, but on windy days poor thermopile stability sometimes caused the abandonment of measurements.

The irradiance was calculated by dividing the value of the electrical power that matched the radiant heating by the area of the limiting aperture and multiplying the result by appropriate correction factors, whose values were approximately as follows.

Correction for reflected radiation	1·005
Correction for thermal resistance of black coating	1·0005
Correction for lead heating	0·997

The correction for reflected radiation was determined from measurements of the spectral reflectances of the receiver, that for thermal resistance from previous measurements (Blevin and Brown 1966), which showed that the factor lay within the range 1·0000–1·0010, and that for heating of the current leads to the electrical element from measurements as described by Gillham (1962).

(*b*) *Absolute Bolometers*

The second type of radiometer was an improved version of an absolute bolometer described by Rutgers (1951). In this instrument (Fig. 5) the receiving element is a 2 cm high vertical strip of 25 μm thick Melinex sheet (polyethylene terephthalate),

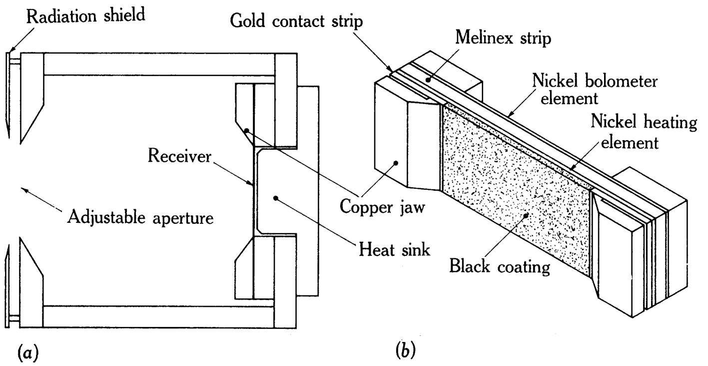

Fig. 5.—Schematic diagram of an absolute bolometer showing (*a*) the complete instrument in horizontal section and (*b*) the receiver drawn to a larger scale, with the thickness of the thin components greatly exaggerated.

whose sides are cut straight to within ± 5 μm and whose ends are clamped with copper jaws, leaving exposed to the radiation a tautly held area of 4 cm by 2 cm. A thin uniform layer of nickel evaporated on the front surface acts as the electrical heating element, and a similar layer on the back as the bolometer sensing element. As with the thermopiles, the heating element is coated with an insulated thin layer of the special gold-black, but, as the nickel-coated Melinex and the gold-black are not fully opaque, a 10 μm thick layer of glossy black paint of low thermal resistance is used as the insulator in this case. The clamping jaws serve as the current leads to the electrical heating element. Great care was taken to minimize any contact resistance between the jaws and the element in order to avoid the large corrections found necessary by Rutgers. The present technique was to evaporate on each end of the nickel element a thick layer of gold of negligible electrical resistance, and to position the ground and polished edge of the jaw to make a pressure contact along a line 0·1 mm from the inner edge of the gold. These steps reduced to much less than 0·1% any errors arising from contact resistance and from uncertainties regarding the exact position of the end of the heating element.

The receiver is housed in a thick-walled aluminium box, having in its front wall a rectangular aperture whose sharply bevelled and adjustable edges are positioned so that they do not mask the receiver from the radiation source but at the same time admit as little unmeasured radiation as possible. Hence with this instrument it is the irradiance of the receiver plane and not that of the front aperture that is measured, and it is the area of the receiver itself that must be known accurately. The unwanted radiation entering the housing either passes the receiver and is absorbed at the back wall or irradiates the tips of the jaws. Although the latter were shaped, highly polished, and gold coated in order to reflect this radiation away from the element, it was found necessary to measure small corrections for light scattered onto the sensitive area. The sensitivity of the receiver, though approximately uniform in transverse directions, varies from zero at the ends to a maximum at the centre. By fitting an appropriate metal heat sink 1 mm behind the receiver it was found possible to improve the uniformity markedly, so that the sensitivity remained at over 95% of its peak value to within $0 \cdot 5$ cm from the jaws.

Three bolometer elements were made and they were used in pairs, the rear nickel elements on the receivers being connected in a Wheatstone bridge whose out-of-balance voltage was observed with a galvanometer amplifier. The approximate characteristics of each bolometer were as follows.

Area of receiver	8 cm^2
Resistance of heating element	20 Ω
Resistance of bolometer element	20 Ω
Current through bolometer element	20 mA
Time constant	4 sec
Sensitivity (for 20 mA bolometer current)	100 mV W^{-1} cm^2
Minimum irradiance detectable	$0 \cdot 5$ μW cm^{-2}

Again the detectivity limit was set by atmospheric variations. The irradiance was calculated by dividing the matching value of electrical power in the heating element by the area of the receiver and multiplying the result by correction factors of approximately the following magnitudes.

Correction for reflected radiation	$1 \cdot 005$
Correction for thermal resistance of black coating	$1 \cdot 0005$
Correction for radiation scattered by jaws	$0 \cdot 999$

The construction of the absolute radiometers will be described in greater detail in a forthcoming National Standards Laboratory Technical Report.

V. Intercomparison of the Radiometers

With the experimental arrangement in Figure 1, the four absolute thermopiles and three absolute bolometers were used in turn to measure the irradiance at 1 m from the lamp, two cycles of measurements being taken. Stability checks on the lamp showed that its radiant intensity drifted during the intercomparison by not more than $0 \cdot 05$% and that short-term fluctuations did not exceed about $0 \cdot 01$%. Table 1 lists the results and also the water vapour pressure at the time of each measurement. To permit a more meaningful intercomparison of the results, all of the irradiance values were adjusted to correspond to a vapour pressure of 8·0 torr, and the bolometer values were increased by 0·05% to compensate for a slight non-uniformity of the radiation field revealed by an investigation with a 6 mm diameter Moll-type thermopile. The means of the adjusted irradiance values for each radiometer are given in the last column of Table 1 and show a scatter of 0·25%, the mean thermopile and mean bolometer values agreeing to within 0·1%.

TABLE 1

INTERCOMPARISON OF SEVEN ABSOLUTE RADIOMETERS

Radiometer	Measured Irradiance (mW cm^{-2})	Atmospheric Water Vapour Pressure (torr)	Adjusted Values of Irradiance* (mW cm^{-2})
Thermopile 1	1·0683	8·1	1·0685
	1·0674	9·7	
Thermopile 2	1·0698	8·2	1·0707
	1·0703	9·6	
Thermopile 3	1·0684	9·7	1·0701
	1·0697	9·3	
Thermopile 4	1·0706	9·8	1·0712
	1·0701	8·6	
		Thermopile mean	1·0701
Bolometer 1	1·0709	7·3	1·0705
	1·0699	7·8	
Bolometer 2	1·0685	7·2	1·0691
	1·0693	8·0	
Bolometer 3	1·0691	7·2	1·0693
	1·0691	7·9	
		Bolometer mean	1·0696

* All values were adjusted to correspond to a water vapour pressure of 8·0 torr. Bolometer values were increased by 0·05% to compensate for non-uniformity of the radiation field.

The various steps in the measurements that might have been significantly in error and the resultant uncertainties in the final irradiance value are assessed as follows.

Distance from filament plane	±0·05%
Limiting area of radiometer	±0·03%
Absorptance of receiving element	±0·05%
Thermal resistance correction	±0·05%
Substituted electrical power	±0·02%
Lead-heating correction (thermopiles)	±0·02%
Scattering by jaws (bolometers)	±0·05%

It is concluded from these considerations that the mean irradiance value is accurate to within about ±0·2%.

The new radiation scale was one of the eight national scales intercompared in the recent project referred to in the Introduction. A report on this international comparison is being prepared for publication by the National Physical Laboratory.

VI. Use of the Radiation Scale

The radiation scale provides a basis for calibrating sources in terms of radiant intensity or detectors in terms of radiant sensitivity. Twelve lamps of the type used for intercomparing the radiometers have been calibrated in conjunction with glass filters as substandards providing a known irradiance. These may be used directly to calibrate radiation detectors and, with any linear and moderately non-selective detector, to calibrate sources of similar spectral energy distribution. When a source of markedly different spectral distribution is to be calibrated against the substandards, either the detector used must be highly non-selective or the spectral sensitivity of the detector and the spectral energy distribution of the source must be known.

As use of the absolute radiometers is tedious, it is anticipated that direct measurements with them will be infrequent. Moreover, the bolometers are fragile and their permanence cannot be assured (and their main purpose has been fulfilled in confirming the accuracy of measurements made with the absolute thermopiles). The absolute thermopiles are more robust and should be usable for many years, although it might prove necessary to renew the gold-black coatings at intervals. We have some inconclusive evidence of slow changes in such coatings, probably due to aggregation of the gold particles.

The radiometers are not intended to be used directly for measuring high irradiances, such as those encountered in meteorology, but they can be used to calibrate secondary instruments such as Moll thermopiles, which are known to give a linear response for irradiances up to 100 mW cm^{-2} or higher.

VII. Acknowledgments

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