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Temperature measurement —

Part 5: Guide to selection and use of radiation pyrometers

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Contents

Foreword

This Part of BS 1041 has been prepared under the direction of the Industrial Process Measurement and Control Standards Policy Committee. It is a revision of BS 1041-5:1972 which is withdrawn. It should be noted that the title has been restyled for consistency with other Parts of BS 1041.

Compared with earlier editions of BS 1041-5, less prominence is given to visual pyrometers as these are not so widely used as hitherto. Measuring circuits are explained in less detail as this guide is intended to assist the user in the selection of the appropriate measurement system rather than the designer of instruments.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 34, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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0 Introduction

Radiation pyrometers measure temperature by radiation methods. The characteristics of the available types of pyrometer, the detectors and optical systems employed, signal treatment, calibration, the advantages and limitations of radiation pyrometers, and some precautions necessary in their application, are explained in this guide. Conditions of temperature measurement vary so widely that it is not possible to provide strict guidance but it is hoped that a user will find sufficient information in the guide to assess the available options and ultimately, in discussion with a supplier, to choose the most appropriate measurement system.

1 Scope

This Part of BS 1041 gives guidance on the selection of radiation pyrometers for use in scientific and industrial environments.

NOTE The titles of the publications referred to in this guide are listed on the inside back cover.

2 Definitions

NOTE Only basic definitions are given. For example the terms emissivity, reflectance and absorptance are defined, but the special cases of the hemispherical, directional, diffuse, specular and total have been left to be qualified as the occasion demands. For these terms the definitions are not complete unless the geometric and spectral conditions are included. General metrological definitions are given in BS 5233.

For the purposes of this Part of BS 1041, the following definitions apply.

2.1
thermal radiation

electromagnetic radiation emitted by an object by virtue of the thermal motion of the atoms and molecules of which it is composed

2.2
radiation pyrometer

generic name for an instrument for measuring the temperature of an object by means of the thermal radiation emitted by the object

NOTE An alternative synonymous term used is “radiation thermometer”.

2.3
full radiator or blackbody

thermal radiator which absorbs completely all incident radiation, whatever the wavelength, the direction of incidence or the polarization, and which emits, for any wavelength, the maximum spectral concentration of radiation for a thermal radiator in thermal equilibrium at a given temperature. Its emissivity is unity

NOTE Other synonymous terms used are “black body” and “Plankian radiator”.

2.4
grey body

thermal radiator whose spectral emissivity is less than unity but is independent of wavelength over the range considered

NOTE An alternative synonymous term used is “non-selective radiator”.

2.5
radiant flux, ϕ

power emitted, transferred or received in the form of radiation

2.6
radiant exitance (at a point of a surface, M)

quotient of the radiant flux leaving an element of the surface containing the point, by the area of the element

NOTE The expression “thermal radiant exitance” indicates that the flux considered is produced by thermal radiation.

2.7
full radiator temperature

temperature of a full radiator at which it has the same thermal radiant exitance as the radiator considered

NOTE An alternative synonymous term used is “full radiation temperature”.

2.8
radiant intensity (of a source, or an element of a source, in a given direction), I

quotient of the radiant flux leaving the source, or the element of the source, propagated in an element of solid angle containing the given direction, by the element of solid angle

2.9
radiance, L

the quotient of the radiant intensity in the given direction of an infinitesimal element of the surface containing the point under consideration, by the area of the orthogonal projection of this element on a plane perpendicular to the given direction

2.10
spectral radiance (L_λ)

the quotient of the radiance L, taken over an infinitesimal range of wavelength, λ, by the range; i.e.

$$L_\lambda = \mathrm{d}L/\mathrm{d}\lambda$$

NOTE An alternative synonymous term used is “spectral concentration of radiance”.

2.11
radiance temperature (of a thermal radiator for a wavelength)

the temperature of a full radiator for which the radiance at the specified wavelength has the same spectral concentration as for the radiator considered

NOTE Use of the term "brightness temperature" is discouraged.

2.12
emissivity, ϵ

ratio of the thermally emitted component of the radiant exitance of the radiator to that of a full radiator at the same temperature

2.13
reflectance, ρ

ratio of the reflected radiant or luminous flux to the incident flux

2.14
transmittance, τ

the ratio of the transmitted radiant or luminous flux to the incident flux

2.15
absorptance, α

the ratio of the absorbed radiant or luminous flux to the incident flux

2.16
filter

a device which is used to modify by transmission the radiant or luminous flux, the spectral distribution, or both, of the radiation passing through it

NOTE A distinction is made between "selective filters" and "non-selective (neutral) filters" according to whether they do or do not alter the relative spectral distribution of the radiation.

2.17
comparison pyrometer

pyrometer establishing the equality of the radiation from the source whose temperature is required with that from a comparison source at a known temperature

2.18
visual pyrometer

comparison pyrometer in which the detector is the human eye

2.19
spectral luminous efficiency, or visibility function (V_λ)

relative spectral sensitivity of the standard eye (see Table 1, BS 4727-4:Group 01 and Figure 4 of this guide)

2.20
objective pyrometer

radiation pyrometer which employs a detector other than the human eye

2.21
total radiation pyrometer

radiation pyrometer which measures all the thermal radiation received from the source

2.22
ratio or two-colour pyrometer

a pyrometer which determines temperature by measuring the ratio of the spectral radiances of the source at two distinct wavelengths

3 Principles of radiation pyrometry

3.1 Introduction

All bodies emit radiant energy as a result of atomic and molecular agitation. The temperature of a body is a measure of the mean kinetic energy of its composite particles in their various modes of motion, and the radiant energy arising from the motion of the particles and emitted from the surface can therefore be used to measure the temperature of the body.

In practice radiation pyrometry can be a convenient means of determining temperature in both laboratory and industrial environments. One of the most important advantages of the method is that the pyrometer need not be brought into the hot zone and so it is free from the effects of heat and chemical attack that often cause other measuring elements to deteriorate in use. There is no theoretical limit to the temperature that can be measured. In practice, considerable problems arise above about 4 000 K, as all materials are then gaseous and optically transparent at most wavelengths.

Radiation pyrometers are more expensive than thermocouples, so tend to be used only in circumstances which can justify the extra cost; for example, in furnaces in which frequent replacement of thermocouples would be necessary, where the temperature of a moving surface is required, or where high accuracy has to be attained. It should be noted that, in general, a correction has to be made for the emissivity of the hot surface if the true temperature is needed.

3.2 The laws of radiation

The radiation within an isothermal cavity exists in a state of dynamic equilibrium with the atomic particles that form the cavity wall. The level of radiation at which this equilibrium occurs depends only on the temperature of the cavity and not at all on its composition, nor on its shape. The radiation within a uniform temperature enclosure is called "full" or a "blackbody" radiation.

Planck showed that the radiation emitted per unit solid angle from unit area in a uniform temperature enclosure in a direction normal to that area, in the range of wavelengths between λ and λ + dλ, is $L_\lambda d\lambda$ where:

$$L_\lambda = c_1 \lambda^{-5} [\exp(c_2/\lambda T) - 1]^{-1} \quad (1)$$

L_λ is called the spectral radiance of the blackbody. The two constants c_1 and c_2, the first and second radiation constants, may be written as $2\pi hc^2$ and hc/k, respectively, where h is Planck's constant, c is the velocity of light, and k is Boltzmann's constant. The value of c is 3.7418×10^{-16} W·m² The value of c_2 is specified in the International Temperature Scale of 1990 to be 0.014388 metre kelvin.

The Wien formula, in which the – 1 in the denominator of equation (1) is omitted, is mathematically more convenient to use:

$$L_\lambda = c_1 \lambda^{-5} \exp(- c_2/\lambda T) \quad (2)$$

If $\lambda T < 3 \times 10^{-3}$ metre kelvin the Wien formula applies with less than 1 % deviation from Planck's law and can therefore be used for most purposes.

The spectral distribution of thermal radiation is shown in Figure 1, in which the spectral radiance and the wavelength are both plotted on logarithmic scales. The curves are all of closely similar shape, reaching maxima such that $\lambda_{max.}\ T = 2\ 898$ μm·K. This is Wien's displacement law, and it is indicated by the dotted line in Figure 1.

The total radiance is obtained by integrating $L_\lambda d\lambda$ over all wavelengths, which leads to Stefan's law:

$$L = \sigma T^4 \quad (3)$$

where

σ is the Stefan-Boltzmann constant.

3.3 Emissivity

In all opaque bodies the space within and between the atoms is occupied by full radiation. However, as the radiation passes out of the surface some of it is reflected back into the interior, so that all surfaces emit less than a full radiator would at the same temperature. The fraction of full radiation that is actually emitted is called the emissivity of the material. Since the reflectance of a surface is the same for radiation approaching the surface from either side, the emissivity ϵ_λ at a wavelength λ is related to the reflectance ρ_λ by the simple relation:

$$\epsilon_\lambda + \rho_\lambda = 1 \quad (4)$$

If the absorptance is α_λ, then also:

$$\alpha_\lambda + \rho_\lambda = 1 \quad (5)$$

Consequently ϵ_λ and α_λ are equal, which is Kirchhoff's law.

The emissivity of a surface depends partly on the nature of the material of which the surface is composed and partly on the smoothness of the surface. If there are no indentations in the surface of a size comparable with or greater than the wavelength of the radiation considered, the emissivity would be entirely related to the material of the surface. A surface that is not smooth and flat will emit more radiation than one that is, because the emitted radiation will be augmented by radiation reflected from other parts of the surface.

A general definition of emissivity is given in **2.12**. The emissivity at a particular wavelength is called "spectral emissivity" and when all wavelengths are taken into consideration the term "total emissivity" is used.

The emissivity of a surface varies with the angle of emission but the variation is small for angles not exceeding 45° to the normal to the surface and it is generally adequate to use the "normal" emissivity without further consideration. The values of emissivity quoted in the context of pyrometry are usually values of normal emissivity. If measurements are made at glancing angles it should be remembered that emissivity may differ from normal emissivity, and that the radiation will probably be strongly polarized. The emissivity averaged over all directions is called the "hemispherical emissivity". It is this value that has to be used in heat loss calculations.

3.4 The emissivity of materials

The emissivity is a function of the optical properties of the substance and for a non-conductor it is a function of the refractive index n:

$$\epsilon_\lambda = 4\ n_\lambda/(n_\lambda + 1)^2 \quad (6)$$

The refractive indices of most inorganic compounds lie in the range 1.5 to 4.0 and metallic oxides usually fall within the range 2.0 to 3.0. Consequently, many industrial surfaces have emissivities in the range 0.96 to 0.64. Non-metallic substances have emissivities that generally do not vary greatly with temperature or with wavelength, except that some are transparent to visible and near-infrared radiation and therefore emit very little at these wavelengths.

Metals behave quite differently from non-metallic substances. The emissivity of a clean metal surface is always low; many metals have emissivities of 0.35 to 0.40 for red light. Metals such as copper, silver, gold and aluminium, that are very good electrical conductors, may have much lower emissivities. The spectral emissivity of metals becomes lower at longer wavelengths and nearly all metals have emissivities less than 0.10 at 10 μm. The spectral emissivities of metals in the visible and the near infrared do not change greatly with temperature. The total emissivity of metals increases with increasing temperature because more of the radiation is of shorter wavelengths at higher temperatures. Transparent substances such as silica and alumina (in the near infrared) have total emissivities that decrease with increasing temperature, because larger proportions of the radiation lie within the transparent region.

The most difficult surface to measure is a metal surface covered by a layer of oxide so thin as to be partially transparent. Such surfaces occur on freshly heated steel, but more persistently on non-ferrous metals. The most difficult of all is probably aluminium.

Values of emissivity for some important surfaces are discussed further in **11.5**.

3.5 Radiation exchange and emissivity errors

To illustrate the problems introduced by the exchange of radiation between objects, and the emissivities of radiating surfaces, consider a pyrometer consisting of a detector D at a temperature T_o in an enclosure at the same temperature. The enclosure defines a field of view for the pyrometer, as indicated in Figure 2, which is filled by a radiating surface R at a temperature T. The total radiant exitance of this surface is the sum of the emitted thermal radiation and that reflected fraction of the radiation from the surroundings S, which are at a temperature T_s. At a particular wavelength, the radiant exitance is:

$$\epsilon_\lambda L_\lambda(T) + \rho_\lambda L_\lambda(T_s) \tag{7}$$

For thermal detectors, the response is determined from the difference between this received radiation and that radiated by the detector, which, with the enclosure, may be taken to act as a blackbody, so that:

$$L_\lambda = \epsilon_\lambda L_\lambda(T) + \rho_\lambda L_\lambda(T_s) - L_\lambda(T_o) \tag{8}$$

Substituting for ρ_λ from equation (4) and rearranging gives:

$$L_\lambda = \epsilon_\lambda\ L_\lambda(T) - L_\lambda(T_o) + (1 - \epsilon_\lambda)\ L_\lambda(T_s) - L_\lambda(T_o) \tag{9}$$

The temperature of the surface measured by the pyrometer will not be the true surface temperature unless either its emissivity is unity, i.e. it acts as a full radiator, or the temperature T_s of the surroundings is the same as that of the surface, in which case the whole system acts as a full radiator. In both cases:

$$L_\lambda = L_\lambda(T) - L_\lambda(T_o) \tag{10}$$

and for $T_o \ll T$, the term $L_\lambda(T_o)$ may be neglected. In all other cases, an error is introduced. If T_s is small, the temperature measured is low, because ϵ_λ is less than unity. As T_s increases, the value obtained increases, tending, in the limit, to T_s whatever the surface temperature.

It is clear that in general an assessment has to be made of the surface emissivity for a hot surface in cold surroundings. The uncertainty in temperature introduced by an uncertainty $\Delta\epsilon_\lambda$ in the emissivity ϵ_λ of the surface may be estimated using the Wien approximation as:

$$\Delta T/T = -\ (c_2/\lambda T)^{-1}\ \Delta\epsilon_\lambda/\epsilon_\lambda \tag{11}$$

The sensitivity of the pyrometer to uncertainties in the emissivity and in the measured spectral radiance is dependent on the magnitude of the factor $c_2/\lambda T$ (which has to be substantially greater than unity for the Wien approximation to be valid, see **3.2**. It may be increased by working at shorter wavelengths, but in practice this possibility is strictly limited by the concomitant rapid decrease in the spectral radiance, see Figure 1). For example, at a wavelength of 650 nm and a temperature of 1 500 K (1 227 °C), the factor is 15 and the error ΔT produced by an error of 10 % in the emissivity, or in the pyrometer output, would only amount to about 0.7 %, or 10 K.

3.6 Colour temperature and ratio pyrometers

The temperature of a full radiator can be measured by determining the ratio of the radiances at two different wavelengths. A pyrometer operating on this principle is called a ratio pyrometer or a two-colour pyrometer, see **6.2.3**. A ratio pyrometer sighted on a grey body (i.e. a body whose emissivity does not vary with wavelength) also measures its true temperature without any emissivity correction. It is emphasized that few real surfaces are even approximately grey in this sense.

If the radiances of a full radiator at a temperature T and at wavelengths λ_1 and λ_2 are L_1 and L_2 respectively, we can apply Wien's formula and write:

$$L_1/L_2 = (\lambda_2/\lambda_1)^5 \exp\ \{(c_2/T)\ (1/\lambda_2 - 1/\lambda_1)\} \tag{12}$$

If the ratio L_1/L_2 is plotted against temperature the curve will be simply proportional to that of a monochromatic pyrometer measuring radiation of wavelength λ', where:

$$\frac{1}{\lambda'} = \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \tag{13}$$

If the surface is not a full radiator nor a grey body but has emissivities ϵ_1 and ϵ_2 at wavelengths λ_1 and λ_2, then the apparent temperature T_c (which is called the colour temperature) is defined by the equations:

$$L_1/L_2 = (\epsilon_1/\epsilon_2)\ (\lambda_2/\lambda_1)^5 \exp\{(c_2/T)\ (1/\lambda_2 - 1/\lambda_1)\} \tag{14}$$

and

$$L_1/L_2 = (\lambda_2/\lambda_1)^5 \exp\{(c_2/T_c)\ (1/\lambda_2 - 1/\lambda_1)\} \tag{15}$$

Hence

$$\frac{1}{T} - \frac{1}{T_c} = \frac{(1/c_2)\ (\ln \epsilon_1 - \ln \epsilon_2)}{(1/\lambda_1 - 1/\lambda_2)} \tag{16}$$

This equation may be compared with the corresponding equation for a radiance pyrometer that measures at one wavelength λ_1 and indicates an apparent temperature T_1 given by:

$$\frac{1}{T} - \frac{1}{T_1} = \frac{\ln \epsilon_1}{c_2/\lambda_1} \tag{17}$$

Since the emissivity of a metal decreases with increasing wavelength it will be seen that the colour temperature of a hot metal is normally greater than its true temperature while its radiance temperature is always lower than the true value.

3.7 Effective wavelength

In the application of the simple Planck and Wien laws to the determination of the temperature of a source, it is assumed that the optical bandwidth is negligible. For many practical pyrometers, especially in those applications requiring good accuracy, this assumption is not valid.

In fact, all pyrometers measure radiation in a finite band of wavelengths. Instead of analyzing the response of a pyrometer by integrating over this band, it is more convenient to determine a weighted mean value called the "effective wavelength", such that the response is the same as that of a pyrometer with the same physical characteristics, but sensitive only to radiation at that wavelength.

The response of a pyrometer is determined by the transmittance τ_λ of the optical system, principally derived from the optical filter, and the spectral sensitivity s_λ of the detector. In a visual pyrometer the visibility function of the eye takes the place of the spectral sensitivity of the detector.

For a pyrometer measuring the ratio of intensities between temperatures T_1 and T_2, the mean effective wavelength λ_m is that for which:

$$\frac{L_{\lambda_m}(T_1)}{L_{\lambda_m}(T_2)} = \frac{\int_0^\infty s_\lambda \tau_\lambda L_\lambda(T_1)\, d\lambda}{\int_0^\infty s_\lambda \tau_\lambda L_\lambda(T_2)\, d\lambda} \tag{18}$$

If T_2 is made to approach T_1 very closely we find a limiting value of the effective wavelength λ_e which applies to a single temperature T, and which is given by:

$$\frac{1}{\lambda_e} = \frac{\int_0^\infty (1/\lambda)\, s_\lambda \tau_\lambda L_\lambda\ (T)\, d\lambda}{\int_0^\infty s_\lambda \tau_\lambda L_\lambda\ (T)\, d\lambda} \tag{19}$$

The effective wavelength is a function of temperature, decreasing slowly with increasing temperature. The variation is greater if the response band is broad.

The effective wavelength should be used in equations derived with the assumption of narrow bandwidth. For example, from the Wien law the response characteristics of a pyrometer that has an effective wavelength λ_e can be expressed as:

$$\ln L_\lambda = \mathrm{A} - c_2/\lambda_e\, T \tag{20}$$

where

A is a constant.

This formula is of course applicable only to pyrometers operating at sufficiently short wavelengths for Wien's formula to be valid.

4 Advantages and limitations of radiation pyrometers

4.1 Introduction

It has been shown that the temperature of a body can in principle be deduced from the amount of radiation it emits. Operationally radiation pyrometers are clearly very different from contact thermometers, and some of their advantages and limitations are enumerated in **4.2** and **4.3**.

4.2 Advantages

The advantages of radiation pyrometers are as follows.

a) Since a non-contact method is employed, no part of the instrument need be brought into the hot zone. As a result, radiation pyrometers are capable of measuring temperatures far beyond the range of all but the hardiest thermocouples without suffering deterioration through heating or chemical attack.

b) Good sensitivity can be achieved even at modest temperatures. At long wavelengths (e.g. 8 μm to 14 μm) measurements can be made down to – 50 °C or even lower. The operating wavelength or waveband of a pyrometer, which is determined by the optical components and detector, can be chosen to suit a particular temperature range or application (see **6.2.1**).

c) The source may be large or small, physically inaccessible or otherwise not susceptible to contact measurement. Since contact is avoided the temperature of the object under measurement is relatively unaffected by the measurement process.

d) Moving objects, for example on a production line, can be viewed.

e) Portable, hand-held instruments are available.

f) Fast response can be achieved, and hence rapid temperature changes can be monitored.

g) In common with contact thermometers, an electrical output is available which can be linearized, recorded or used for control purposes.

4.3 Limitations

The limitations of radiation pyrometers are as follows.

a) The radiation emitted by an object is dependent on the surface emissivity, and this is in general dependent on temperature, wavelength, angle of view and surface condition. If the emissivity is not known well enough, special techniques may have to be employed.

b) A considerable contribution to the detected signal may be due to radiation reflected from the target surface. This is usually unfortunate, although some "emissivity compensated" pyrometers make use of reflected radiation, and the Kirchhoff law (see **3.3**), in their operation.

c) Radiation pyrometers should be calibrated either using a source whose radiance in the relevant wavelength range is known, or by comparison using a calibrated pyrometer of the same effective wavelength.

d) The signal may be dependent on the nature of the medium between the source and the detector. Water vapour, carbon dioxide, haze, smoke and dust, for example, can cause errors by partially absorbing or reflecting the radiation. Similarly the transmission of any window or other component between the target and the pyrometer will have to be taken into account, and the target should fill the field of view.

e) First costs are often higher than for an equivalent contact measurement system, and as with all temperature measurement, a certain skill and training of operators is needed. The choice of the most appropriate pyrometer for a particular purpose has to be carefully made.

f) Changes in ambient temperature may affect the measurement, and in industrial environments water or air may be needed for cooling the instrument or purging the atmosphere.

Some of the precautions which should be observed in using radiation pyrometers are discussed in clause **11**.

5 Classification of radiation pyrometers

5.1 Introduction

Because there are many types of radiation pyrometer, each with its own advantages and often designed for a specific purpose, it is useful to attempt a classification before proceeding to detailed descriptions. Classifications based on continuously varying parameters such as temperature and wavelength are likely to be of only transitory value, since they would require modification as optical design and detector performance improve. The two main classifications which are followed here are based on the wavelength selection principle and on method of operation. These alone will not be sufficient to specify the instrument required for a given application, which would of course depend on temperature and wavelength ranges, accuracy and resolution, signal treatment, whether the instrument is to be portable or fixed, and any other special requirements.

5.2 Classification by wavelength selection principle

Classifications by wavelength selection principle are as follows.

a) *Total radiation pyrometers*. These are sensitive to the major part of thermally-emitted radiation. Their response may be characterized by Stefan's law (see **3.2**)

b) *Broadband radiation pyrometers*. This type is sensitive to radiation over a broad band of wavelengths, but the response cannot be related to either Stefan's or Planck's law (see **3.2**). Instead the relationship between the output signal and the temperature of the source has to be established by calibration. The spectral range is usually restricted by the short wavelength cut-off of the Planck function and the long wavelength cut-off of the detector or window.

c) *Narrow-band or spectral radiation pyrometers*. The response of this type of pyrometer is limited to a single narrow band of wavelengths by the inclusion of an optical filter, and hence Planck's law can be applied. This class includes several of the more popular instruments, including the visual or disappearing filament pyrometer, and the wide range of photoelectric pyrometers.

d) *Two-colour or ratio pyrometers*. These instruments attempt to compensate for errors which arise from the emissivities of real surfaces by measuring the ratio of the spectral radiances in two narrow bands at different wavelengths. It is, however, necessary to assume that the source behaves as a grey body or to assume a value for the ratio of the spectral emissivities at the two wavelengths.

e) *Multi-wavelength pyrometers*. These extend the principle of the previous class to several wavelength bands. It is necessary to make further critical assumptions about the behaviour of the source emissivity with wavelength and temperature. A small computer may be needed to analyse the signals from each spectral band.

5.3 Classification by method of operation: direct-reading and comparison pyrometers

As the name implies, direct-reading pyrometers relate to the output signal from the radiation detector directly to the temperature of the radiating source. They consist essentially of an optical system, a detector and an amplification and display system. They are relatively simple and robust. However, the temperatures measured are only accurate if the detector is stable and its output a function only of the incident radiation intensity. Many detectors do not satisfy these requirements, and have to be used in the comparison mode, in which the unknown source temperature is obtained by comparison with a stable reference source. This is often a small tungsten filament lamp, placed inside the pyrometer itself. The alternative, a blackbody reference source, is usually too cumbersome, has too long a response time and requires too much power for general use. Blackbody sources are found, external to the pyrometer, in research and industrial applications where accurately predictable spectral radiances are essential. One example of a comparison pyrometer with an internal lamp is the disappearing filament visual pyrometer.

There are many advantages in employing a null detection system, giving zero output when the test and reference sources match. The balance point is independent of the characteristics of that part of the pyrometer common to both sources, including the detector. Also, changes in the gain of the amplifier, and other electronic effects, cancel out. In addition, the test and reference sources are often compared by chopping the radiation from them so that they each alternately illuminate the detector. The out-of-balance signal is therefore approximately a square wave, and a.c. amplification and filtering techniques, with phase-sensitive detection, may be used to reduce the effects of thermal noise, interference and drift.

Occasionally, the difference between the outputs from two detectors, separately illuminated by the two sources, is measured and nulled. This technique does not, however, possess the same freedom from common errors as that employing the a.c. null detection technique.

Non-linear amplifiers may prevent saturation and loss of the a.c. signal when the sources are far from balanced. Nulling may be achieved manually, by minimizing the output from the a.c. detection system. Alternatively, the pyrometer may be made automatic by feedback from the phase-sensitive detector. If this is taken to the reference source, for example the current supply to the filament lamp, the pyrometer follows the source temperature. If the signal is taken to the electrical supply to the source, it is possible to control the source to follow a fixed or programmed temperature determined by the reference lamp.

6 Principal types of radiation pyrometer

6.1 Total and broadband pyrometers

The design of total radiation pyrometers is generally based upon the combination of a mirror optical system with a thermal detector (see clause **7**). The characteristic feature of the thermal detector is the potentially wide spectral range, and a pyrometer using this type of detector is therefore particularly suitable for sources at comparatively low temperatures, at which most of the emitted radiation is beyond the range of uncooled photon detectors. The advantage of far infra-red response is to some extent offset by the low intrinsic sensitivity of thermal detectors, and their susceptibility to extraneous thermal effects, draughts and changes in atmospheric pressure. The effect of background radiation may also be significant. If the pyrometer is completely non-selective, with no window, the response will be proportional to ($T^4 - T_o^4$), where T_o is the background temperature.

Broadband pyrometers fall into two main classes: those, like total radiation pyrometers, with thermal detectors but whose spectral response is significantly limited by an absorbing window or other optical component, and those with photon detectors in which the waveband is limited by the response of the detector or an optical component. In both cases, if the T_o term can be neglected, an empirical equation of the form:

$$L = A\,T^n$$

can usually be used to relate the output of the pyrometer to the source temperature. It is, however, necessary to establish different values for A and n to cover different temperature ranges, and it is better in practice to relate the detector output to temperature using a series, preferably including an exponential term.

6.2 Narrow band, or spectral, pyrometers

6.2.1 *Photoelectric pyrometers*. This group of instruments covers a wide variety of combinations of different detectors, lens and mirror optical systems, and operation in both the direct-reading and comparison modes. In addition, it is usually possible to select an operating wavelength appropriate to the particular application. For example, many photoelectric pyrometers operate at about 655 nm in order to calibrate standard lamps for use with visual pyrometers, which are normally restricted to this wavelength. As may be seen from Figure 1, the sensitivity of a spectral pyrometer is greater the shorter the wave-length, because of the factor $c_2/\lambda T$. This factor should be 10 or greater (see **3.5**). Thus spectral pyrometers are intrinsically more sensitive than total or broadband pyrometers, where the equivalent factor may only be 4. Wavelengths in the visible range are suitable for accurate measurements of high temperatures, above about 800 °C. At lower temperatures, down to ambient, it is necessary to utilize infra-red wavelengths in order to obtain a satisfactory signal-to-noise ratio.

The operating wavelength is normally established by the inclusion of an optical filter, which may take the form of a coloured glass or an interference or mesh filter, placed at a convenient point in the optical path. It is of course necessary to select a detector with reasonable sensitivity at the chosen wavelength. The spectral response curve of the detector may play a useful part in reducing the contribution to the output signal from radiation at wavelengths far from the operating wavelength, which could otherwise give rise to sizeable errors in the measurement of sources with varying emissivity.

If the transmission characteristics of the optical filter and the response characteristics of the detector are known, it is possible to measure the radiance temperature of a source by measuring the ratio of the spectral radiance of this source to that of a second source at a known or reference radiance temperature, by application of the Planck law. If the source is a blackbody, or its emissivity at the chosen wavelength is known, then the true temperature can be calculated. Photoelectric pyrometers are used as the standard instruments for measurements of the highest accuracy, and the application of the Planck law is specified as the means of realizing the International Temperature Scale of 1990 (ITS-90) for temperatures above the freezing point of silver (961.78 °C), using as the reference source a blackbody at the freezing point of silver, gold (1064.18 °C) or copper (108.62 °C) according to choice. A reproductibility of 0.01 °C or better can be achieved at these points. Photoelectric pyrometry has also been used successfully at lower temperatures, especially at wavelengths in the near infra-red, and good consistency with the ITS-90 (here realized using platinum resistance thermometers) can be achieved.

While photomultipliers are often employed in this type of instrument, they are too cumbersome and delicate for industrial equipment. For this, solid state detectors are suitably robust. Silicon photodiodes, which are sensitive to radiation at visible wavelengths and up to 1 μm, may form the basis of pyrometers with a working range rather similar to that of visual pyrometers. For applications at lower temperatures, pyrometers containing the various infra-red detectors are available. In some cases, the operating wavelength may be selected to coincide with a region of high emissivity from the particular surface whose temperature is being measured. For example, 3.43 μm corresponds to the C-H stretching frequency in organic materials, so that this wavelength is often chosen to measure the surface temperature of plastic objects or films.

Similarly, when measuring the temperature of glass, it is possible to measure either the bulk or the surface temperature by choosing the appropriate infra-red wavelength.

6.2.2 *Visual pyrometers*. Visual pyrometers of the disappearing filament type are widely used in industry and in laboratories. An image of the filament of an internal reference lamp is superimposed upon that of the source. The current through the filament is varied until a luminance match is obtained, and the section of the filament image against the source "disappears". The human eye, used here as a detector, suffers from a number of non-linear and time-dependent defects, the results of which are minimized by this direct comparison method.

A typical optical system of a high precision disappearing filament optical pyrometer is shown in Figure 3.

The objective lens O forms an image of the source in the plane of F, the filament of a small lamp. The field consisting of the filament F superimposed on the image of the source is viewed through a Ramsden or Huygens eyepiece and the erecting lens G. A Ramsden eyepiece is shown in the diagram. An aperture D_1, which is fixed in position relative to the filament, is placed between the objective lens and the filament to define the entrance cone of radiation and is as near to the objective as possible. The angle α subtended by this aperture at the filament is known as the entrance angle of the pyrometer. A second aperture D_2 is placed between the erecting lens and the eyepiece. The optimum position is coincident with the image of D_1 in the lens G: deviations from this position will result in the brightness of the field falling off towards the periphery when the aperture is moved away from the ideal position. The angle β subtended by the effective diameter of lens G at F is the exit angle of the telescope. The aperture D_3 is the field stop and is placed at the focal point of the eyepiece. The aperture D_4 is the pupil of the observer's eye.

A neutral filter N, which reduces the luminance of the image of the source, enables the instrument to be calibrated in higher temperature ranges. It may be placed at any convenient position between the filament and the source. The so-called monochromatic screen M is usually a red glass filter and is placed in any convenient position between the filament and the observer's eye.

The pyrometer lamp has an important influence on the design and performance of a disappearing filament optical pyrometer. Round wire tungsten filaments about 0.04 mm diameter are commonly used in pyrometer lamps, but high grade instruments are fitted with lamps having flat ribbon filaments about 0.04 mm wide, which have the advantages of greater uniformity of temperature along the length of the filament, with smaller ambient temperature effects at low luminosities, small thermal inertia and fast response, low current consumption, and larger limiting angles in the optical system with a consequent gain in field brightness and resolving power. In the more precise forms of pyrometer the lamp has flat sighting windows of good quality glass. The part of the filament at which matching should be effected is indicated by a pointer built into the lamp, or by the bend of a hairpin-shaped or M-shaped filament. The lamps are usually of the vacuum type. They should be aged at a radiance temperature of about 1 700 °C for 15 h in order to stabilize them.

The effective wavelength of a disappearing filament pyrometer is determined by equation 18 with the visibility function, V_λ, in place of s_λ (the spectral sensitivity of the detector) and using transmission of the red glass filter for τ_λ, see Figure 4. The instrument is usually designed so that the effective wavelength is 650 ± 10 nm and this value is generally assumed for the purpose of calibration. If, however, the effective wavelength differs by $\Delta\lambda$ from 650 nm, then the error in calculating the corrections is given by:

$$\Delta T - T_R^2 \ln \epsilon \, \Delta\lambda / c_2$$

Thus if $\Delta\lambda = 10$ nm and $\epsilon = 0.4$, $\Delta T = 2$ °C at a radiance temperature of 1 600 °C (1 873 K). In the most accurate applications it will be necessary to take account of the change in effective wavelength with temperature.

Disappearing filament pyrometers may be used from 700 °C to 3 500 °C or higher, in two or three ranges. It is sometimes suggested that the range may extend downwards by removing the filter. However temperatures measured in this way may be seriously in error, as they depend more critically upon the eye response of the operator and the spectral emissivity of the surface.

6.2.3 *Ratio pyrometers*. If the spectral emissivity of an object is constant within a particular wavelength range, i.e. it acts as a grey body within this range, it is possible to eliminate the error from this source by measuring the ratio of the spectral radiances at two separate wavelengths, thereby cancelling the effects of the unknown emissivity. This principle forms the basis of the ratio or two-colour pyrometer, as was discussed in **3.6**. In practice the ratio may be obtained by placing two detectors in the beam, with a different optical filter in front of each, or by switching the filters alternately in front of a single detector. Both arrangements are similar to those employed in comparison pyrometers and, in the latter case, the advantages of a.c. amplification and detection can be realized. It is also possible to feed back the difference between the two signals in order to adjust a variable compensating filter in the optical path. The position of the filter such that the difference is reduced to zero is a measure of the temperature of the source.

The separation of the wavelengths of the two channels of a ratio pyrometer is not critical, although if they are too close the difference between the two signals will approach the detector noise level, and if they are too widely separated, the pyrometer becomes sensitive to the differences in the characteristics of the optical components in different wavelength regions.

The effectiveness of a ratio pyrometer depends critically upon the validity of the basic assumption regarding emissivity. Whereas emissivity errors in most pyrometers are related to the uncertainty in the value of the emissivity itself [see equation (11)] in this case they are related to the uncertainty in $d\epsilon/d\lambda$. Moreover, since in two-colour pyrometry one is measuring the ratio of two signals, both of which are positive functions of temperature, the intrinsic sensitivity of the method is necessarily less than that of a monochromatic pyrometer in the same wavelength range.

That is to say, a given uncertainty in the radiance measurement (from whatever cause) will lead to a larger corresponding uncertainty in temperature. However, the method can be of value for aluminium surfaces, since the emissivity does not vary greatly with wavelength and measurements with a monochromatic pyrometer may be complicated by emissivity variations as the surface roughens and oxidises. In the case of many steels $d\epsilon/d\lambda$ is large, and a monochromatic pyrometer is likely to give better accuracy.

Apart from the possibility of reducing errors due to the emissivity of the surface, a ratio measurement may also be useful when the size of source is likely to vary, or if the sight path may be partially obscured, for example by steam, smoke or dust. The effect on the measured temperature is largely removed if the variation in the radiance is independent of the wavelength. However, for steam, smoke or dust this is unlikely to be the case if the particle size is of the same order as the operating wavelengths of the pyrometer. Similarly, if emissivity variations occur the reading will be unaffected only if the emissivity ratio at the two wavelengths remains the same.

6.3 Emissivity and background compensation

6.3.1 *Emissivity compensated pyrometers for specularly reflecting surfaces*. In these instruments the output of the detector when viewing an internal source is compared with that when viewing the target irradiated by the internal source. The temperature of the internal source is varied until the two outputs are equal. The temperature is inferred from the power supplied to the internal source, and since the sum of the spectral emissivity and spectral reflectance of the target surface must be unity [equation (4)] the result is independent of the emissivity. In practice a chopper is used to cause radiation from the internal source to be detected alternately with the combined radiation direct from the target and from the internal source after one reflection. The instrument is then used as a null system with a.c. detection, and the performance is largely determined by the stability of the internal source. The method can only be applied to surfaces whose diffuse reflectance is low.

6.3.2 *Emissivity compensation using a hemispherical reflector*. It is possible to make surface temperature measurements on both specularly and diffusely reflecting surfaces that are practically unaffected by the emissivity of the surface, provided this exceeds about 0.6, by using a pyrometer with a hemispherical reflector. The pyrometer head has a hemispherical concave mirror attached to it, the radiation passing through a small window at the apex of the hemisphere to the detector. The hemispherical mirror, which is gold plated to make it a good reflector of infra-red radiation, is put close to the hot surface. The surface is then surrounded by its own reflection in the hemispherical mirror, forming an approximation to a blackbody enclosure.

Full radiation at the temperature of the surface passes through the window to the detector. As the reflected radiation heats the surface under the reflector, the reading must be taken quickly. The method can be used for surface temperatures up to 1 300 °C, but unlike other techniques it requires good access to the surface.

6.3.3 *Two-sensor pyrometry*. With modern improvements in microprocessor analysis it has become feasible to adopt a "two-sensor" system in which the principal measurement is made with the radiation pyrometer sighted on the target in the usual way, and a subsidiary measurement is made of the "background" temperature using either the pyrometer itself, or a second radiation pyrometer or a thermocouple.

The background reading is used to make a correction to the principal measurement. As equation 9 shows, one still needs to know the emissivity, unless $T = T_s$, and the method is therefore "background corrected" rather than "emissivity compensated". Its usefulness partly depends on how well the background temperature is characterized by the auxiliary measurement, but it has been applied successfully under a variety of industrial conditions.

6.3.4 *The use of cavities*. The calibration table supplied with a radiation pyrometer by the manufacturer, unless otherwise stated, will be for measurements made when the pyrometer is sighted on to a blackbody. For a surface whose emissivity is less than unity, but known and constant over the required temperature range, the true temperature may be calculated, or indicated directly by the appropriate setting of the emissivity control.

If these conditions cannot be achieved, errors due to reflection and emissivity can be largely eliminated by sighting the pyrometer into a cavity in the object whose temperature is required. Provided that the cavity is deep enough, blackbody conditions will obtain within it and the radiation pyrometer will then indicate the true temperature. The requirement for the ratio of the depth of such cavity to its diameter is dependent on the accuracy sought and the emissivity of the surface. The depth of cavity in this context is obviously the length, measured from the closed end, over which the temperature is uniform.

The emissivity of a closed-ended cylindrical tube having a surface emissivity of 0.4 and ratio of length to diameter 5, is 0.993[1]. Equation 11 shows that the temperature measured by a pyrometer having an effective wavelength up to 1 µm sighted into such a cavity would be in error by less than 0.1 % of the temperature up to 1 500 °C because of this departure from blackbody conditions. A total radiation pyrometer in the same circumstances would have an error less than 0.3 % of the temperature.

As an illustration to satisfy the above conditions using a sillimanite target tube 80 mm in diameter in a furnace having a wall thickness of 300 mm, the minimum length of tube required would be 300 + (5 × 80), i.e. 700 mm.

Some reduction in minimum overall length of a target tube can be obtained in such circumstances if the wall thickness can be effectively reduced in the area surrounding the tube. It is sometimes necessary to do this to prevent damage by the change which could occur if the tube protruded too far into the furnace.

Ceramic target tubes have lower resistance to impact and thermal shock than metal tubes and when required, should be installed and used with care. Silicon carbide tubes are less susceptible to thermal shock than other types of ceramic tubes.

7 Detectors

7.1 General

Detectors used for radiation pyrometers fall into two main groups:

a) thermal detectors, which utilize the temperature rise resulting from the absorption of thermal radiation. Their spectral response may be made independent of wavelength over a very wide range.

b) photon detectors, whose characteristics are determined by the absorption of individual photons. Their response is limited to a relatively narrow wavelength range, dependent upon the electronic band structure of the photosensitive material involved.

In addition, the human eye is employed in visual pyrometers.

7.2 Detector characteristics

7.2.1 *Properties*. A number of properties of detectors have to be known in order to design pyrometers and to determine their working range. These are described in **7.2.2** to **7.2.4**.

7.2.2 *Sensitivity and noise*. The response characteristic of a detector is normally expressed in terms of the electrical output, either voltage or current, obtained under specified conditions for each watt of incident radiation. For thermal detectors, the radiation is taken to be the total radiation from a blackbody at a specified temperature, even though the detector may not be sensitive at every wavelength. For photon detectors, the peak or maximum sensitivity for monochromatic radiation is often quoted. The photo-sensitive area and the field of view are also required in order to match the device to the optical system of the pyrometer, and to estimate the electrical output of the detector for given source temperatures.

A lower limit to the measurement of temperature is set by the background noise in the output signal. In most pyrometric detectors, this arises from thermal effects either within the detector or from thermal radiation within its field of view. It may therefore be reduced by cooling the detector. This, in fact, is essential for photon detectors operating at infra-red wavelengths near the maximum of room temperature blackbody radiation (10 µm). If the residual noise is determined by the level of external radiation, the detector is said to be "background limited". This noise component may be reduced by placing cooled apertures or windows in front of the detector to limit the effective field of view to that required by the pyrometer design.

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[1] See Quinn, T.J. "The calculation of the emissivity of cylindrical cavities giving near black-body radiation", Brit. J. Appl. Phys. 1967, Vol 18, p.1105. The first-order approximation for the emissivity of a cavity, ϵ_c, made of a material of diffuse reflectivity ρ, and with length-to-diameter ratio D, is:

$$\epsilon_c = 1 - \rho/4D^2$$

This expression should only be used to obtain a rough magnitude of ϵ_c for values of D greater than 5.

Quantitatively, the detector noise is given as the root mean square value of the electrical output in a bandwidth of 1 Hz at a specified frequency and under typical operating conditions. For white noise, this is proportional to the square root of the bandwidth, so that it may be expressed in units of volts (or amperes) per square root bandwidth, i.e. $V \cdot Hz^{-1/2}$. For practical purposes, the noise equivalent power (NEP), which is the amount of radiative energy required to give an output signal of the same amplitude as the noise, is a convenient indicator of detector performance. It has been found, both theoretically and in practice, that the NEP is proportional to the square root of the photo-sensitive area of the detector. A useful figure of merit for the performance of detectors is therefore the area-normalized detectivity, denoted by D^*, equal to the square root of the detector area divided by the NEP in $cm \cdot Hz^{1/2}W^{-1}$. It is necessary to specify the conditions under which this has been measured, i.e. the blackbody temperature for thermal detectors or the wavelength for photon detectors, the frequency at which the signal and noise are measured, and the bandwidth employed. It is conventional to normalize measurements to a bandwidth of 1 Hz.

7.2.3 *Stability*. If the output of a detector is dependent within the required accuracy, only on the intensity of the radiation incident upon it, the calibration of the pyrometer may be expressed simply in terms of the electrical output as a function of the radiance temperature of the source. Some influences, for example that of the ambient temperature, may be reduced by compensating mechanisms or electronic circuitry. Others, fatigue in the photodetector for example, can only be reduced or estimated with great difficulty. If these produce changes or errors which may exceed the specified uncertainty, it is necessary to operate the pyrometer as a comparator, that is, as a device which can compare the radiance from the source with that from an internal or external reference source, whose calibration is known and stable.

For pyrometers with an electrical output, it may be necessary to know the relationship between the incident intensity and the output voltage or current, for example, in order to apply the equations given in clause **3**. In many cases the response is linear, and the output is directly proportional to the intensity.

7.2.4 *Response time*. Although the response time of the detector is not often a critical factor in pyrometer design, it is often relevant to the range of applications which can be handled by the instrument. The surface temperature or emissivity of an object, especially if it is moving, may fluctuate rapidly. Some pyrometers are designed to detect the maxima or minima in the measured signals, and these have to have a response time less than the duration of the fluctuations, otherwise an averaged signal is obtained. In comparing pyrometers, the test and reference sources are often compared by switching the detection system from one to the other. The maximum rate at which this can be carried out is determined by the response time of the detector, and this limits the total response time of the pyrometer. At low frequencies, the NEP tends to increase as other sources of noise add to the thermal noise within the detector.

7.3 Types of detector

7.3.1 *The eye as a detector*. As with any type of radiation detector the two most important features of the eye are its absolute sensitivity to the radiation falling upon it, and its relative spectral sensitivity. The response curve of the eye, generally known as the visibility function, is given in Figure 4. The maximum sensitivity occurs at 555 nm and the cut-off is at 430 nm in the blue and at 700 nm in the red end of the visible region. The sensitivity of the eye is such that the lower limit of a visual pyrometer is at about 700 °C, while above about 1 300 °C it is necessary to protect the eye from glare and to this end an absorption filter is used to reduce the apparent intensity of the source.

7.3.2 *Thermal detectors*

7.3.2.1 *General*. The operation of thermal detectors depends upon the temperature rise produced by the absorption of thermal radiation. This may be measured by conventional temperature sensors, such as thermocouples, thermopiles or resistance thermometers (usually thermistors of a special design) or using other temperature-dependent effects, such as charge generation as in pyroelectric detectors. Conventional sensors may be attached to metal discs in order to increase the sensitive area, although the response time will be lengthened as a result. The absorbing surface may be blackened in order to decrease the reflectance. Such detectors can possess a flat spectral response over a very wide wavelength range and hence are ideally suited for use in total radiation pyrometers. Although the spectral sensitivity is much less than the peak values achieved by photon detectors, a blackened thermal detector is sensitive to a much greater fraction of the total thermal radiation emitted by a source and can therefore be used to measure temperatures down to room temperature or below.

The temperature of the detecting element rises until the rate of heat loss is equal to the radiant power absorbed. Heat is lost by gaseous conduction and convection, by conduction through Wires and supports, and by re-radiation. Gaseous conduction and convection are usually the major contributors to heat loss, unless the detector is evacuated. Re-radiation losses are generally small.

The response characteristic of the detector is dependent on the temperature rise and on the temperature sensitivity of the detecting element (and, for a thermopile, on the number of detecting elements). The response time of the detector is dependent on the thermal capacity and diffusivity of the detecting element, and is typically long, especially as compared with photon detectors. If heat losses from the element are reduced so as to increase the sensitivity, this may have a deleterious effect on the response time.

To take advantage of the broad spectral bandwidth, thermal detectors are best used with reflecting optical systems rather than lenses, which tend to cut off in the infra-red where thermal radiation is at its most intense. In practice, the spectral range is often limited by the need to include windows in the pyrometer to protect sensitive elements of either the optics or the thermal detector. The results of truncation of the spectral range are two-fold; first, Stefan's law is no longer obeyed, and an arbitrary relationship between radiated power and blackbody temperature has to be established. Second, the error arising from a lack of knowledge of the emissivity of real surfaces is much more difficult to analyze and to correct for. Some special designs of pyrometer have been introduced in an attempt to minimize these effects.

In order to prevent changes in the ambient conditions interfering with the measurement, most thermal detectors are operated in a differential mode. In the case of thermocouple or thermopile detectors, the reference or cold junctions are placed in thermal contact with the case of the device, and the temperature difference between this and the thermally isolated absorbing surface carrying the measuring junctions is measured. Bolometers, which are detectors measuring a resistance change in a sensor, may employ two small flakes of thermistor material, one exposed to the incident radiation, the other shielded from it, in a resistance bridge configuration which compensates for fluctuations in the ambient temperature. In general, good compensation is more difficult to achieve at low levels of incident radiation, and under these circumstances it may be desirable to thermostat the enclosure.

7.3.2.2 *Pyroelectric detectors*. A pyroelectric detector consists of a permanently electrically polarized dielectric material, often in crystalline form, connected as a capacitor. The heating effect of absorbed thermal radiation produces a change in the distribution of charge which may be detected as a change in the voltage across the device by a high input impedance amplifier. As excess charge leaks away gradually, this detector has to be used to measure changes in the level of thermal radiation, rather than the absolute level. The incident signal is therefore normally chopped at a low audio-frequency to provide a convenient signal for a.c. amplification. Polarized materials in common use at present include triglycine sulphate (TGS), lithium tantalate ($LiTaO_3$), lithium niobate ($LiNbO_3$) and lead zirconate tantalate (LZT).

Pyroelectric detectors are usually sensitive to fluctuations in the atmospheric pressure, i.e. they are microphonic, but using two elements may provide some compensation from this effect as well as from changes in the ambient temperature. The absorbing surfaces of pyroelectric detectors are usually blackened in order to increase the range of spectral sensitivity.

7.3.3 *Photon detectors*

7.3.3.1 *Photoemissive detectors*. Photons incident upon certain photosensitive materials will cause the emission of electrons into a vacuum. These may be collected by an anode positively charged with respect to the emitting material, or photocathode, to give a photocurrent proportional to the number of photons striking the photocathode each second. This simple device constitutes a vacuum photodiode. A more common and valuable photodetector — the photomultiplier — is obtained when special electrodes called dynodes are introduced between the cathode and the anode. These increase the photocurrent by the process of secondary multiplication. With potential differences of about 100 V between adjacent dynodes, a modern photomultiplier will give an overall gain of up to 10^6 or 10^7. As the total transit time is small, about 30 ns, it is possible to record the detection of single photons at the photocathode with the fast output pulses at the anode.

The response times of photomultipliers are determined by the variations in the transit time for individual photoelectrons, and are characteristically between 1 ns and 10 ns. In many applications, the pulses of electrons arriving at the anode are smoothed electronically to produce a d.c. current. The secondary multiplication process is essentially noise-free, and the main source of noise in the output of photomultipliers used for radiation pyrometry originates in the thermionic emission from the photocathode. As the thermionic work function is generally between 1 eV and 2 eV, the background noise level may be reduced to very low levels, about 10 output pulses/s for each square centimetre of photocathode area (corresponding roughly to a photocathode current of about 2×10^{-18} A), by cooling the photomultiplier to a temperature between – 20 °C and – 80 °C.

The spectral sensitivity is often characterized by the quantum efficiency of the photocathode, i.e. the ratio of photoelectrons emitted to the number of incident photons. The useful spectral range is determined by the electron band structure of the cathode material, and usually shows a sharp cut-off at the long wavelength end corresponding to the bandgap energy. The upper limit to photomultiplier response lies at present at 1.4 μm, cathodes then becoming difficult to prepare and are of limited stability. The sensitivity of the output of a photomultiplier to changes in its ambient temperature is determined mainly by the change in the quantum efficiency of the photocathode. This is typically of the order of 0.1 %/°C to 0.3 %/°C, but varies, in sign as well as magnitude, with the photocathode type, the ambient temperature and the wavelength of the incident radiation. With some photocathodes, it becomes very large in the long wavelength cut-off region.

In several respects photomultipliers are cumbersome to use in industrial instruments. They require a high voltage supply, between about 800 volts and 2 600 volts, and a resistance divider network for the dynode voltages. They are sensitive to magnetic fields, and have to be screened, and they may be damaged by vibration and mechanical shock. They tend to be used only in pyrometers of the highest accuracy required for research or calibration laboratories.

7.3.3.2 *Semiconductor detectors*. In a simple semiconductor material, it is possible for photons of sufficient energy to excite electrons from the valence to the conduction band. These, as well as the “holes” left in the valence band, increase the conductivity of the material, enabling it to be used as a photoconductive detector. if the photon absorption occurs near a p-n junction, the charge carriers may be collected by the junction electric field to produce a detector photocurrent. In both cases, a long wavelength cut-off occurs at photon energies corresponding to the bandgap difference between the valence and conduction bands. If it is required to detect radiation at longer wavelengths than is possible with simple semiconductors, excitation from levels close to the conduction band which occur in impurity or complex ternary semiconductors may be employed. To some extent the response of ternary photodetectors may be tailored by adjusting the relative proportions of the constituent elements. The major source of semiconductor noise results from the thermal excitation of electrons into the conduction band. As the spectral response is extended into the infra-red by reducing the photon energy required, the noise level at a given temperature will tend to increase rapidly. For a given photodetector, the noise level roughly doubles for each 10 °C rise in its temperature. To achieve good sensitivity for photon detectors, therefore, it becomes increasingly important to cool them as their operating wavelength increases.

It is apparent from the preceding paragraph that semiconductor detectors may be either photoconductive or photovoltaic. In fact, many semiconductor materials may be made in both forms, although some cannot easily be made into photodiodes. Relative spectral sensitivities for some photon detectors, including a type S-20 photo-multiplier, are shown in Figure 5. The ambient temperature coefficients of the sensitivity of semiconductor detectors is relatively small, of the order of 0.1 %/°C to 0.3 %/°C, and may vary in both magnitude and sign with wavelength.

8 Optical systems

8.1 Introduction

The aims of the design of the optical systems, which are more or less common to all pyrometers, are:

a) to isolate the required band or bands of wavelengths;

b) for a given source area, to increase the proportion of radiation incident upon the detector, which is usually small;

c) to reduce the effect on the output of changes in the distance between the source and the detector, and;

d) to remove interference from radiating sources outside the desired field of view.

8.2 Aperture optics

If a detector is exposed to the radiation from an extended but finite source, not only does the signal from it depend on the distance of separation, but the presence of other sources in the vicinity may affect the reading. These effects may be overcome by placing an aperture stop and a field stop between the source and the detector, as shown in Figure 6, in such a way that all rays arriving at the detector arise from some point on the source.

It will be seen from Figure 6 that the extreme rays AB and CD define the extent of the source AC which is used when the detector has an effective size BD. For a given aperture and field stop geometry, the distance R can increase until the limiting rays move to the edge of the source. If the source is small and the required range of R has to be large, the aperture stop would have to be small, resulting in a low output and loss of accuracy. This difficulty can be overcome by the use of a lens to image the source on to the field stop.

Aperture optics are only used in pyrometers for measuring either high temperatures, in which case the low optical throughput is compensated by the high radiance, or the average temperature of a large surface.

8.3 Lens optics

In a lens system, such as that in Figure 7, the point of intersection of the limiting rays has now moved up to the lens, so that a smaller source can be measured without reducing the diameter of the aperture stop. The detector output depends on the solid angle subtended at the aperture stop by the field stop, and on the area of the aperture stop.

The focal length of the lens should be such that the image completely covers the field stop. It is not essential for the image to lie in the plane of the detector but it is important for all rays reaching the detector to originate from the hot source. A reflected radiation stop, or glare stop, is sometimes necessary in order to prevent diffracted and stray radiation, reflected from the casing of the instrument, from reaching the detector. The overall sensitivity of the instrument varies with the angular field of view of the pyrometer. At a given distance a smaller source may be focused by using a lens of longer focal length, but the sensitivity is reduced unless the aperture of the lens is correspondingly increased. Chromatic and spherical aberrations should always be taken into account when calculating the minimum target size required.

Lenses are normally made of glass but other materials are used depending on the temperature range being measured. As the temperature to be measured increases, the energy maximum of the emitted radiation moves towards shorter wavelengths, and glass lenses may be used. For lower temperatures, it is necessary to use lenses of vitreous silica or other materials. The transmissions of typical materials are given in Table 1.

8.4 Mirror optics

It is generally the case that lenses do not pass a sufficiently high fraction of the thermal radiation from them to be used in total radiation pyrometers, which therefore often employ mirror optics. Figure 8 and Figure 9 show typical arrangements of single and Cassegrain mirror imaging systems. An eyepiece is generally fitted at the rear to facilitate directing the pyrometer at the hot body and focusing its image so that it completely covers the detector.

Mirrors reflect a high proportion of the incident radiation over a wide wavelength range. They have metallic surfaces chosen for this property and for freedom from tarnishing. These surfaces may be either formed on solid metal, or deposited as films on glass substrates. It is, however, necessary to protect the mirror surface from dust and fumes. In some cases, where the atmosphere is relatively clean and continuous measurements are not required, a protective cap may be fitted, which is removed only when measurements are to be made. In dirtier conditions, and where continuous recording is essential, a protective window should be fitted as shown to make the enclosure dust tight. This should be chosen from the same range of materials as are lenses (see Table 1) and should be made as thin as possible to minimize the amount of radiation absorbed.

8.5 Fibre optics

Fibre optics, both rigid and flexible, are commercially available with adequate transmission for incorporation in the optical system of a radiation pyrometer. Such pyrometers are particularly useful in applications where the hot surface cannot be viewed directly because of obstructions, or where the pyrometer would otherwise have to be in a chemically, thermally or electromagnetically hostile environment (see Figure 10 and Figure 11).

The optical head can be built to withstand temperatures of 200 °C to 400 °C, much higher than those at which detectors can operate. If these temperatures would otherwise be exceeded, air or water cooling may be employed, or alternatively the radiation can be focused on the fibre tip by a lens, both being kept at an acceptable temperature, as in Figure 11. This would also give better target definition compared with the arrangement of Figure 10.

The transmission of silica-based fibres becomes progressively poorer beyond 1.5 µm, and applications at temperatures below about 600 °C have therefore to employ a fibre of a different material or some form of optical stimulation. Techniques are evolving in which effects in the fibre itself, such as temperature-dependent back-scattering, are used to produce a distributed temperature sensor, as well as those in which the fibre is a passive transmitter of, for example, stimulated fluorescent emission from a sensor material at the fibre tip. At higher temperatures fibres made from single-crystal sapphire have been used to sense temperatures up to 2 000 °C. By coating the fibre tip with an opaque material, a small blackbody source is produced whose radiation is piped directly to a second, conventional fibreoptic system.

8.6 Sighting

It is normally possible to have optical sighting through a pyrometer system, provided that the lens or window is transparent to at least part of the visible spectrum. For pyrometers intended for fixed operation this may not be necessary because the initial positioning and alignment can usually be carried out with sufficient accuracy. For portable pyrometers it is essential to have a sighting system, either through the lens, an auxiliary telescope or by pistol sights.

9 Signal treatment

The output signal from a pyrometer is often unsatisfactory for indicating, recording or control. This may be due to one or more reasons which are detailed below. It is usually possible to modify the raw signal to obtain a suitable output. This is normally done by one or more modules contained in a processor situated remote from the pyrometer. The available modules include the following.

a) *Linearizer*. The raw signal is always non-linear (often very non-linear) with target temperature. The linearizer produces an output which is linear with temperature which can then be displayed on an indicator or recorder without the need for special scales and charts. If the output is scaled to, for example, 1 mV/°C and a suitable offset is added, the resulting output can be displayed as temperature on a suitable digital voltmeter.

b) *Emissivity*. Pyrometers are, almost without exception, calibrated to read correctly when viewing a blackbody source. Without correction for the emissivity of the surface the pyrometer reads low. This is corrected by multiplying the output by a factor $1/\epsilon$, and most commercial pyrometers incorporate an emissivity adjustment.

c) *Averager*. The raw signal may show considerable short term variations. These may be real (i.e. due to temperature variations of the surface viewed) or false, but in either case the signal is not suitable for indication or control. The averager smoothes the signal so that short term variations are eliminated.

d) *Peak-picker*. The true signal level may be present intermittently either because the target is not always present or because of periodical obstructions in the sight path. The peak-picker holds the output at the level corresponding to the highest input recently acquired. A slow decay (adjustable to suit the application) is provided to prevent the retaining of the highest input ever received during a measurement period.

e) *Valley-picker*. This is the reverse of the peak-picker. The lowest input is held subject to a slow rise. This circumstance of the lowest temperature being required is very seldom encountered.

f) *Sample-and-hold*. The desired temperature may not be that of the hottest or the coolest surfaces seen in a short period. This applies to several cyclical processes. A command signal from the process instructs the sample-and-hold module either to follow the input (when the desired target is seen) or to hold the signal unchanged (when the desired target is not seen). The held signal does not need to decay since it will be updated in the next sample period.

g) *Alarm*. Relay contacts change over when the signal is above a pre-set high level or below a pre-set low level.

h) *Output*. Extra outputs in current or voltage form are provided for additional display or for control purposes.

i) *"Hot target" detector*. This senses the presence or absence of a hot target and supplies a yes/no signal.

Signal treatment is usually available in the form of electronic modules which can be tailored to suit each type of pyrometer and combined to give the desired system performance.

10 Calibration

10.1 Introduction

Radiation pyrometry differs in many respects from the more familiar methods of temperature measurement. Factors such as the wide choice of operating wavelength and optical bandwidth make the technique more complex, both in theory and in practice. However, the situation may be simplified in one respect. All pyrometers should be calibrated against sources which may be treated as blackbodies. Thus the effects and errors arising in many applications from the emissivities of real surfaces are not of concern in calibration.

10.2 The ITS-90

All measurements of temperature which need to be reliable and reproducible should be traceable to the established International Temperature Scale of 1990, ITS-90. This is based upon the assignment of numerical values to the temperatures of a number of fixed points; that is, the temperatures corresponding to phase changes in pure elements and compounds, such as the triple point of water, 0.01 °C, and the freezing points of certain pure metals.

Up to the freezing point of silver (assigned the value 961.78 °C, or 1234.93K) the ITS-90 specifies the use of platinum resistance thermometers calibrated at these fixed points to realize the scale. Above this temperature it specifies the application of the Planck law using as the reference source a blackbody at the freezing point of silver, gold (1064.18 °C) or copper (1084.62 °C) according to choice. Above the silver point the temperature of a source is determined on ITS-90 by using a (photoelectric) pyrometer to measure the ratio Q of its spectral radiance to that of a blackbody at the chosen reference point. In the Wien approximation (equation 2) the unknown temperature (in kelvins) is calculated from:

$$\text{In } (Q) = c_2\,(1/T_\text{o} - 1/T)/\lambda_\text{e} \qquad (22)$$

where T_o is the reference temperature, also expressed in kelvins. The result will be independent of the effective wavelength λ_e of the pyrometer, provided that the bandwidth of the pyrometer is sufficiently narrow.

Since many photoelectric pyrometers operate with best accuracy only as comparators, the scale is often maintained on standard sources. These, and transfer standard pyrometers are now discussed.

10.3 Blackbody sources

Blackbody sources suitable for the calibration of pyrometric instruments generally consist of a cavity of high emissivity held in a temperature-controlled enclosure, such as a bath of circulating liquid or a tubular furnace. This type of source is essential for the calibration of broadband and total radiation pyrometers, since corrections for the variations in spectral emissivity of other sources cannot be made with sufficient accuracy. The blackbody calibration is normally referred to a contact thermometer placed just behind the radiating surface of the cavity as viewed through the aperture. Modern cavities are generally based on cylindrical designs, which are simple to construct, heat and measure. They should have roughened or grooved walls and re-entrant or angled end-surfaces. A lower limit to the emissivity of the cavity resulting from its geometry and the emissivity of the material of which it is constructed can usually be calculated without much difficulty by adopting a simple model for its design. The error ΔT produced by a deviation $\Delta\epsilon$ from ideal blackbody conditions is given by:

$$\Delta T = (\lambda T^2/c_2)\Delta\epsilon \qquad (23)$$

The apparent emissivity of a cavity will also depend upon the temperature gradient along its length. Again, the effect can be estimated by calculation. More importantly, if there is a temperature gradient there will also be a temperature difference between the blackbody and the contact thermometer. The presence of a gradient may be detected by plotting the temperature of the thermometer as a function of its depth of immersion into the blackbody. Departures from a constant value may originate from two causes: from the temperature gradient itself, and from heat flow along the thermometer, which changes the temperature registered by the thermometer at a given point. If the curve obtained does not show a plateau at the operating position of the thermometer, the associated errors may be large. Unfortunately, the converse is not always true, as the measurement procedure may itself alter the gradient.

For these reasons it may be preferable to calibrate the blackbody source as a complete system using a previously calibrated radiation pyrometer, and subsequently to use the thermometer reading, or any other suitable variable such as the power supplied to the system, to infer the temperature, although it may be necessary to correct for changes in the ambient or cooling water temperature. Direct calibration removes the error given by equation (23) and should reduce that due to temperature gradients, at least at the calibration wavelength. However, if the source is calibrated at a wavelength λ_0 and then used at a wavelength λ_1, there will still be an error ΔT_1, given by:

$$\Delta T_1 = (\lambda_1 - \lambda_0)\ (T^2/c_2)\ \Delta\epsilon \qquad (24)$$

assuming that the source behaves as a grey body.

Blackbody sources can be designed to operate with pyrometers requiring a wide range of target sizes, and they are particularly useful at moderate temperatures, under 1 000 °C, where the stability of contact thermometers raises relatively few problems in the short or medium term. However, they may be expensive to manufacture, cumbersome to transport, and are often of limited life, especially at very high temperatures.

10.4 Standard lamps

Tungsten strip lamps are commonly used for the dissemination of ITS-90 between 700 °C and 2 300 °C, the temperature being given as a function of the current flowing through the filament. They are available in evacuated or gas-filled versions. The former are more stable, as gas convection effects are absent, but are limited to temperatures below about 1 700 °C because of evaporation of the filament. The calibration below 1 000 °C is slightly dependent upon ambient temperature. Because the emissivity of tungsten is less than unity, the real temperature T of the surface is greater than its apparent temperature T_R, since:

$$1/T_R = 1/T + \lambda_e \ln(\epsilon_\lambda)/c_2 \qquad (25)$$

Thus at 660 nm, and T_R equal to 2 100 K (1 825 °C), the true surface temperature of the tungsten strip would be about 2 000 °C. T_R is called the spectral radiance or brightness temperature, and is equal to the temperature of a blackbody producing the same radiance at that wavelength. Because the second term varies with wavelength, the calibration of a standard lamp also depends upon the wavelength. It is normally specified to lie in the range 645 nm to 665 nm, as the lamps are often employed to calibrate disappearing filament pyrometers whose effective wavelength is about 650 nm.

To overcome the wavelength dependence, and to enable higher radiance temperatures to be attained, a blackbody lamp has been developed. This contains a cylindrical tungsten tube of about 1 mm internal diameter with a bundle of tungsten wires at the centre, which acts as a good blackbody source at the real temperature of the tungsten. Unfortunately the output radiance depends quite strongly upon the viewing angle, and the dependence changes significantly from one lamp to another, and with the radiance temperature. Errors may then be introduced by the use of pyrometers whose apertures or angular sensitivity differ from those employed for the calibration of these lamps. For these reasons, blackbody lamps are only used as standards in the gas-filled version at temperatures from 2 200 °C to 2 650 °C where strip lamps drift rapidly with time.

In summary, lamps have two major disadvantages. Their calibration is valid over a limited wavelength range, although this can be extended, especially if they are provided with windows with higher transmission in the infra-red. They also possess a small target size, the filament normally being 1.5 mm wide. In many applications these factors are more than offset by the fact that they are relatively inexpensive, easily transported albeit rather fragile, and, in most cases, very stable. A vacuum high-stability lamp, for example, will only change by about 0.1 °C to 0.2 °C at the gold point each year with moderate-to-heavy use.

10.5 Transfer standard pyrometers

In most cases, commercially available radiation pyrometers are not suitable for use as dissemination standards, in particular because their resolution and long term stability is inadequate or has not been established. The disappearing filament (visual) pyrometer is in common use, but it is not ideal as a standard. To obtain consistent readings the matching of the filament and the source has to be performed several times, with the filament temperature both increasing and decreasing, and an average of the readings taken. Even then, it is not possible to attain a repeatability of better than 1 °C. The long term stability depends on the performance of the internal lamp, which can be variable and susceptible to change from mechanical shocks. Although the effective wavelength depends on the visual response of the operator, the errors incurred from this source are normally small compared with the total uncertainty in use. However, it is recommended that the same operator both calibrates and uses this type of pyrometer.

A photoelectric pyrometer, with a narrow bandwidth, lends itself more readily to accurate measurement and assessment of uncertainties. For use as a standard, the detector has to be stable in the long term. Only silicon photodiodes have been thoroughly investigated and found to be satisfactory in this respect, but they are insensitive at wavelengths above 1 μm, (see Figure 5) and this limits their operation to temperatures above about 500 °C.

A calibration of a narrow band pyrometer should include a statement of the effective wavelength. In the case of pyrometers with bandwidths of 10 nm or more, such as the disappearing filament type, the variation of effective wavelength with source temperature is not negligible for calibrations of the highest accuracy, and should not be given on the calibration certificate.

10.6 Uncertainties and procedures

The uncertainties in the calibration of lamps arise from a number of sources.

a) Uncertainty in the calibration of the working standard.

b) Measurement errors in the calibration.

c) Size of source correction. Even though a source may be larger than the geometrical target area of the pyrometer and fill its optical system, the measured temperature will depend slightly upon its size. If the surroundings are cold, the reading will be low, and correct only for very large sources. This effect arises from diffraction and scattering present in all pyrometers, and is especially important for small sources such as lamps. While the diffraction component may be calculated from the characteristics of the optical system, the scattering term should be determined experimentally, and is generally found to be the larger.

d) Correction for differences in operating wavelength. As stated above, the calibration of a tungsten strip lamp is valid only at one wavelength. For pyrometers operating at slightly different wavelengths, a correction has to be applied. The change in radiance temperature with wavelength has been calculated from measured values for the spectral emissivity of tungsten, assuming a constant value of 0.92 for the transmission of the lamp window. The result, which is confirmed by experiment, and is applicable for wavelengths between 640 nm and 680 nm, is plotted in Figure 12. To apply the correction, the operating wavelength λ_e of a pyrometer has to be determined, most simply by measuring its response with a monochromator. If the lamp is calibrated at a wavelength λ_0, the correction to be added to the temperature at a given current is:

$$\Delta T = (\lambda_e - \lambda_0)\mathrm{d}T_R/\mathrm{d}\lambda$$

It may be assumed that the uncertainty in this correction is no greater than 20 % of its magnitude.

Additional errors arise from the base temperature coefficient, which need only be measured for vacuum lamps below the gold point, and from the effects of internal and external gas convection currents in and around gas-filled lamps. The combined effect of all of these errors is to produce a total uncertainty which in the best case might be 1 °C to 2 °C for evacuated lamps and 3 °C to 5 °C for gas-filled lamps. It is possible with care to calibrate a lamp with a lower uncertainty, but the extra time required makes this uneconomic for most applications.

The calibration of pyrometers follows a comparison procedure. The stability of the pyrometer is first checked over a period varying from a few hours to several days, depending on its design, at a single temperature. In the case of disappearing filament pyrometers, the filament lamp may be aged overnight. These and other narrow band pyrometers with operating wavelengths close to 655 nm are calibrated directly against standard lamps, and clearly the uncertainty of this procedure is at least that of the standard lamps, plus the setting repeatability of the pyrometer.

For infra-red pyrometers, and those requiring a larger target area than that available from strip lamps, calibration is effected against standard blackbody sources. Again, the total calibration uncertainty depends upon the uncertainties associated with the source and upon the reproducibility and stability of the pyrometer. The stability tests described above establish the magnitude of the latter.

The calibration of a blackbody cavity may achieve traceability to the national standards in one of three ways.

a) If it contains a contact thermometer of suitable long-term stability, this may be calibrated separately, and used to measure the temperature of the blackbody. Suitable sensors would be platinum resistance thermometers, up to about 660 °C, type R or S thermocouples up to about 1 200 °C, and type B from about 800 °C to 1 600 °C. As explained earlier, the main sources of error in this procedure originate from the emissivity of the blackbody and the temperature difference between the effective position of the blackbody and that of the contact thermometer. The latter is particularly difficult to measure, and is often under-estimated. If the combined uncertainty, including the calibration of the sensor, is too large for the particular application, it is necessary to have the complete system calibrated, with the difference between the blackbody temperature and that recorded by the contact thermometer being measured over the working range. This exercise may be inconvenient, in that blackbody systems are often cumbersome and difficult to transport, and it may be expensive if a wide temperature range is required.

b) The blackbody source may be used in conjunction with a suitable calibrated pyrometer. While the operating wavelength of the latter is not critical, it should possess long-term stability and a maximum target size smaller than that provided by the blackbody. If it is to be calibrated by another laboratory, it should be rugged, so that its calibration is not affected by transport to and from the calibrating laboratory.

c) A pyrometer with an effective wavelength of about 655 nm may be used to transfer the temperature scale from a calibrated standard lamp to the blackbody. This method is particularly suitable for temperatures above about 1 000 °C, especially if the laboratory already possesses standard lamps for other purposes. The uncertainty in this procedure is a combination of the calibration uncertainty of the lamp, the resolution or measurement uncertainty of the pyrometer, and the size of source error, if this differs from that obtained with the standard pyrometer. The latter effect can be measured with a set of apertures of differing sizes, but it has been found that it does not vary greatly within the limited range of pyrometers tested.

There is no obvious reason to prefer any one of these procedures: each possesses advantages and disadvantages which vary with the temperature range to be covered, the required accuracy, the existing facilities and equipment.

11 Precautions necessary in the use of radiation pyrometers

11.1 Factors affecting indicated temperature

Most of the factors affecting the temperature indicated by a radiation pyrometer have already been discussed in this guide. They include effects due to:

a) the emissivity of the source;

b) the transparency of the source or any film on its surface;

c) uniform or selective absorption of the radiation by fumes, smoke, dust, water vapour, carbon dioxide, etc., in the atmosphere, by deposits on windows or lenses in the pyrometer or on other components such as furnace windows, in the path of the radiation;

d) the presence of flames;

e) reflected radiation;

f) changes in response characteristics of the detector resulting, for example, from changes in ambient temperature.

It is evident that the contributions of such factors to the total error in the measurement will depend on particular applications and circumstances. Some techniques for minimizing or compensating for these errors have been described, but the selection of the right pyrometer for a given application, and its proper installation should be fully discussed with the supplier.

Some additional precautions which may apply in the use of radiation pyrometers are as follows.

11.2 Process monitoring

In process control and many other situations, repeatability is more important than accuracy. It is then sufficient to rely on an indicated temperature even if this differs from the true surface temperature. The acceptability of this mode of operation naturally depends on the constancy of the relation between the true and indicated temperatures in the short term and from one measurement to the next. This in turn depends on the constancy of the conditions of measurement and the factors listed in **11.1**.

11.3 Installation

The pyrometer, whether fixed or portable, should be held securely and free from vibration in such a position that the detector, or field stop, is completely illuminated by the radiation from the source. Information and advice on field of view, or target diameters at various focussing distances, should be provided by the pyrometer supplier.

There should be no intrusion within the boundary of the limiting rays accepted by the pyrometer by diaphragms or other obstructions between it and the source, otherwise the indicated temperature reading will be low. This is particularly important when the source is small or when sighting a pyrometer down a tube, through a hole, or possibly between the turns of a coil of an induction heater. The table of target sizes given in the manufacturer's specification can be used as a table of aperture sizes at different distances. Apertures should be larger than the specified minimum diameters at the stated distances and the pyrometer head located so that this is so. Proper alignment of the pyrometer head and sighting tubes, when used, should be ensured.

It is advisable to sight the pyrometer at right angles to the hot surface, or within 45° on either side of this position, since at greater angles there may be considerable variations in the radiation emitted. The diameters quoted for minimum target sizes refer to the size measured at right angles to the line of sight. Inclined surfaces should be correspondingly larger.

Wherever possible the pyrometer head should be located in such a position that there is an adequate margin on target and aperture sizes. The pyrometer head should be mounted in a position free from fumes or steam and where splashes of metal or other deposits cannot settle on the protecting window or lens of the pyrometer. The lens or protecting window should be kept clean at all times and care should be taken to avoid scratching the surfaces, especially in the case of arsenic trisulphide materials which are particularly susceptible to scratching. An air purge attachment can be mounted on the front of most radiation pyrometer detector heads to ensure that a clear view of the source is obtained and that nothing is allowed to deposit on the lens or window. The air used for purging should be clean, and one, or occasionally two filters may be required to remove oil and water present in the air supplied.

The quantity of purging air will depend on the conditions and only the minimum necessary to clear the sight path and obtain a steady reading should be used. Too much air may cool the surface being measured, particularly if this is close to the pyrometer head, or even oxidize a clean metal surface so that its emissivity is increased causing a false temperature indication. Recommendations on air flows and pressures are given by the manufacturers of radiation pyrometers.

Water cooling of the pyrometer head is required if the temperature it attains when mounted in the correct position exceeds the limit specified by the manufacturer. Air cooling can be used but it is usually more costly, inefficient and unreliable than water cooling. When air cooling has to be used, the air should be cold. In some industrial applications "cooling air" is often too hot for pyrometer cooling. Cooling air, like purging air, should be reasonably clean.

Copper pipe for the cooling water supply can be connected directly to the water jacket of the pyrometer head but it is preferable to use a short length of flexible armoured tubing for this purpose so that any adjustments in position of the pyrometer head may be readily made when required. It is necessary to install the instrument so that the water jacket is completely filled at all times. Only a small flow of water, say 50 L/h, is required but the flow has to be continuous and not interrupted for more than a few minutes at a time. It is desirable to arrange for some visual or other indication of the continuity of the water flow and, if possible, for an alarm to indicate any interruption in flow.

Particular care should be taken to avoid excessive cooling of the pyrometer head or water may condense on the jacket and on the pyrometer lens and window. To obviate this it is often convenient to warm the cooling water by fixing the inlet water supply alongside the furnace.

The manufacturer's instructions concerning the limits of temperature of operations of the pyrometer head and of the ancillary equipment should be carefully followed. Compensation for high and variable ambient temperatures is included in most pyrometer heads and these will often operate satisfactorily at quite high temperatures (e.g. 100 °C). In general, however, the indicating or recording device will be operating in a position having a much lower ambient temperature than that of the pyrometer head.

Electrical connections between the pyrometer head and the indicating or recording device should be made with suitably insulated copper wire. Compensating cable is not required as ambient temperature compensation is included in the pyrometer head.

It is advisable to allow a sufficient length of lead at the pyrometer head to permit it to be removed from its mounting or water jacket without disconnecting the leads. The connecting cable should not be close to wires carrying alternating current unless adequate precautions are taken to avoid pick-up, e.g. by using a twisted pair of leads or by ferro-magnetic shielding. Screened leads should be used if induction heating units are in the vicinity, and the screen should be earthed and connected either to the casing of the pyrometer head or at the read-out point.

11.4 Absorption by the intervening medium

If some of the radiation emitted by the source is absorbed before reaching the detector, the resulting output will be low. Absorption can be caused by smoke, fumes or water droplets all of which absorb (and scatter) visible and infra-red radiation, and all are easily seen. Such obscuration usually changes rapidly and the pyrometer gives a fluctuating output.

The normal constituents of a clean atmosphere also absorb some infra-red wavelengths. Water vapour and carbon dioxide are of particular interest in radiation pyrometry, with absorptions in the regions of 2.7 µm and 4.3 µm respectively lying within the spectral range of thermal, lead sulphide and indium antimonide detectors. The concentration of carbon dioxide in free air is small and fairly constant, so its absorption may be neglected in most applications. Humidity variations are more significant and absorptions may amount to a few percent of the radiation. The magnitude of the effects depends on the transmission characteristics of the material used for the lens or window, as well as the spectral response of the detector. Thus to limit the variations due to atmospheric absorption to 1 % of the temperature, the distance between source and pyrometer should not exceed:

a) 1 800 mm for a pyrometer with a glass lens;

b) 1 200 mm for a pyrometer with a vitreous silica lens;

c) 600 mm for a pyrometer with an arsenic trisulphide lens.

Readings obtained with such pyrometers will be affected markedly by the presence of flames between the source and the pyrometer, since the water and carbon dioxide bands in this case give rise to emission interference. If there are non-luminous flames the pyrometer should be chosen so as to avoid the absorption bands of these flames; if there are luminous flames, then it is not possible to obtain accurate measurements.

The readings of pyrometers with detectors such as silicon cells responding to radiation of wavelengths not exceeding about 2 µm are unaffected by absorption and emission from water vapour and carbon dioxide. Such pyrometers can be used at distances of 10 m or more from the source, provided that the hot surface is large enough for the radiation from it to cover completely the receiving surface of the detector and that the atmosphere is not unduly dusty. If the target area is obscured by steam or smoke, care has to be taken to clear the sight path.

In those applications where it is necessary to use a window, or prism, between the hot surface and pyrometer (e.g. to maintain a vacuum, a high pressure, or a controlled atmosphere) it should be remembered that the radiation reaching the detector will be reduced by reflection at the window or prism surfaces and sometimes the absorption is also significant. For visual pyrometers and objective pyrometers having detectors sensitive to radiation of wavelengths less than about 1 µm, glass windows or prisms may be used. For pyrometers with thermal detectors and glass lenses, windows or prisms of vitreous silica should be used. Windows or prisms of fluorite should be used with pyrometers having lenses of arsenic trisulphide (or similar chalcogenide glass). It is essential for the pyrometers to be calibrated in conjunction with the window or prism to be used in subsequent temperature determinations.

11.5 Emissivity

The influence of emissivity on radiation pyrometry has been discussed at various points in this guide, and its importance will by now be clear. Most pyrometers include an emissivity control by means of which the radiance temperature is converted to true temperature. This pre-supposes that the appropriate value of the emissivity is known, and it is advisable to discuss the application with the pyrometer manufacturer in order to establish whether values taken from the literature are likely to be accurate enough or, if not, how realistic values should be obtained.

Table 2 gives typical ranges of emissivity values that may be used when correcting readings taken with pyrometers of three common types. A range of values is given because emissivity changes with temperature, with composition and according to the surface conditions. For example "blued" steel may describe steel having quite a wide range of thicknesses of oxide film; the appearance of the surface of oxidized copper is not necessarily a safe guide to its emissivity. The values given for unoxidized metal surfaces are most liable to error, being affected by the slightest film of oxide. If a surface is very rough its emissivity will be greater than the values given in the table, but an emissivity ϵ is not likely to be increased to more than $0.5\,(1 + \epsilon)$.

Table 3 gives the radiance temperature measured by the three types of pyrometer, assuming the effective wavelength to be that given in the table, for different spectral emissivities. The values are calculated from the equation:

$$\frac{1}{T} - \frac{1}{T_{\mathrm{R}}} = \frac{\lambda_{\mathrm{e}}}{c_2} \ln \epsilon$$

Table 4 shows the error in temperature which would arise from an error of – 10 % in the assumed value of emissivity (e.g. 0.72 instead of 0.80) using equation (11) of **3.5**.

Table 1 — Transmission of lens and window materials

Material	Approximate transmission range
	μm
Glass	0.35 to 2.7
Vitreous silica[a]	0.2 to 3.5
Sapphire	0.2 to 6.5
Fluorite (calcium fluoride)	0.2 to 9.0
Magnesia	upper limit 9.0
Arsenic trisulphide[b]	0.6 to 10.0
Silicon	1.5 to 12.0
Germanium	2.0 to 25.0
KRS.5 (thallium bromo-iodide)	0.5 to 40.0

[a] The vitreous silica used should be of the type which does not have an absorption band at 2.73 μm.

[b] This is one of the glasses known as chalcogenide glasses. Other types of these glasses are becoming available with transmission ranges extending to 20 μm.

Table 2 — Typical emissivity values (for guidance only)

Material and condition	Spectral emissivity 0,65 µm		Spectral emissivity 1 µm		Total emissivity	
	polished	rough machined	polished	rough machined	polished	rough machined
Aluminium (25 °C to 600 °C)						
unoxidized	0.15	0.3	0.1	0.25	0.05	0.15
lightly oxidized	0.3	0.4	0.2	0.3	0.1	0.2
heavily oxidized	0.5	0.5	0.4	0.4	0.3 to 0.4	
Copper (100 °C to 1 000 °C)						
unoxidized	0.1	0.25	0.05	0.2	0.03	0.2
lightly oxidized	0.4	0.6	0.4	0.5	0.4	0.5
heavily oxidized	0.8	0.8	0.8	0.8	0.8	0.8
Iron and steel (100 °C to 1 200 °C)						
unoxidized	0.35	0.35	0.35	0.35	0.1	0.25
lightly oxidized	0.5	0.5	0.45	0.5	0.35	0.5
heavily oxidized	0.8 to 0.95		0.8 to 0.95		0.7 to 0.95	
Cast iron (200 °C to 1 000 °C)						
unoxidized	0.35	0.5	0.3	0.5	0.2	0.5
lightly oxidized	0.6	0.75	0.5	0.75	0.5	0.65
heavily oxidized	0.8 to 0.95		0.8 to 0.95		0.8 to 0.95	
Stainless steels (100 °C)						
unoxidized	0.3	0.45	0.3	0.45	0.1	0.3
lightly oxidized	0.5	0.7	0.5	0.7	0.4	0.6
heavily oxidized	0.8 to 0.9		0.8 to 0.9		0.8 to 0.9	
Stainless steels (800 °C)						
unoxidized	0.3	0.45	0.3	0.45	0.3	0.5
lightly oxidized	0.5	0.7	0.5	0.7	0.5	0.7
heavily oxidized	0.8 to 0.9		0.8 to 0.9		0.8 to 0.9	
Carbon (0 °C to 1 500 °C)						
shiny to rough dull	0.8 to 0.9		0.8 to 0.9		0.8 to 0.9	
carbon soot	0.95		0.95		0.95	
graphite	0.75		0.8		0.75 to 0.85	
Alumina						
grain size 1 µm to 2 µm (1 000 °C)	0.2 to 0.4		0.2 to 0.4		0.2 to 0.4	
grain size 10 µm to 100 µm						
(1 000 °C)					0.3 to 0.5	
(1 500 °C)					0.2 to 0.4	
Brick						
common red (20 °C)					0.95	
white refractory (100 °C to 1 000 °C)	0.3		0.3		0.7 to 0.9	
silica (1 000 °C)			0.5 to 0.6		0.75 to 0.85	
Plastic (0 °C to 100 °C)						
transmittance < 0.1					0.7 to 0.95	
transmittance 0.2 to 0.4					0.45 to 0.6	
transmittance > 0.4					0.3 to 0.4	
Paints and lacquers (0 °C to 100 °C)						
oil paints and enamels (white and dark)					0.9 to 0.95	
shellacs and lacquers					0.8 to 0.95	
aluminium paint					0.3 to 0.65	

Table 3 — Variations of radiance temperature with pyrometer effective wavelength and with emissivity

Temperature	0.65 µm			0.9 µm			2.0 µm		
°C	0.4	0.6	0.8	0.4	0.6	0.8	0.4	0.6	0.8
500	—	—	—	467	481	492	431	460	482
1 000	936	964	984	913	950	978	822	894	952
1 500	1 379	1 430	1 469	1 336	1 405	1 457	1 173	1 302	1 408
2 000	1 804	1 887	1 949	1 738	1 846	1 930	1 490	1 684	1 850
NOTE Emissivity values are as in the column headings, 0.4, 0.6 and 0.8.									

Table 4 — Errors in temperature arising from an error of – 10 % in emissivity at three effective wavelengths

Temperature	Error/°C		
°C	0.65 µm	0.9 µm	2.0 µm
500	—	3	8
1 000	7	10	23
1 500	14	20	44
2 000	23	32	72

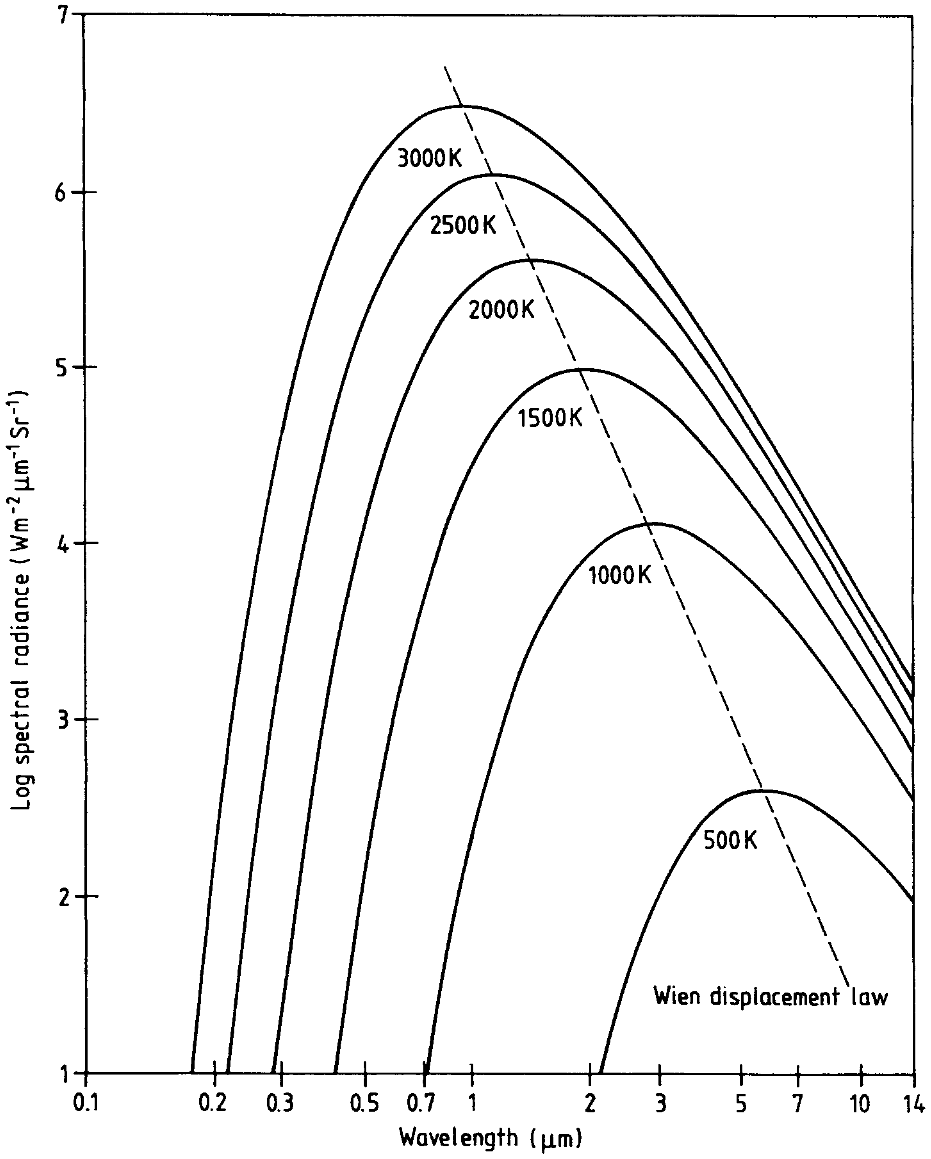

Figure 1 — Spectral radiance of a blackbody as a function of wavelength and temperature

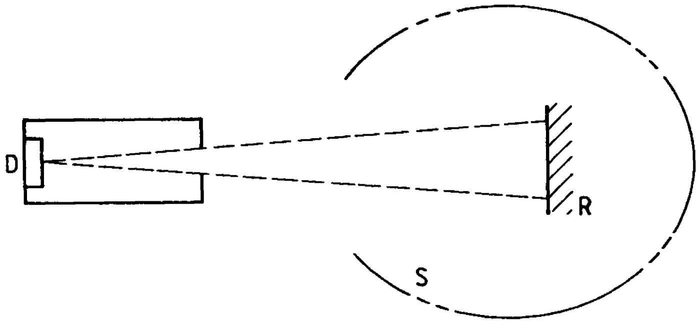

Figure 2 — Schematic arrangement of a pyrometer D, and a radiating surface R in surroundings S

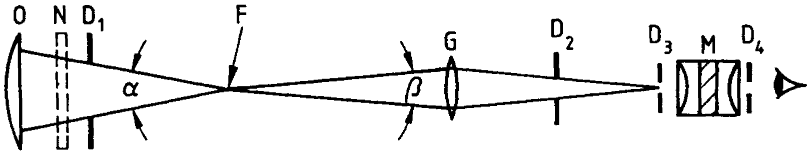

Figure 3 — Optical system of disappearing filament optical pyrometer

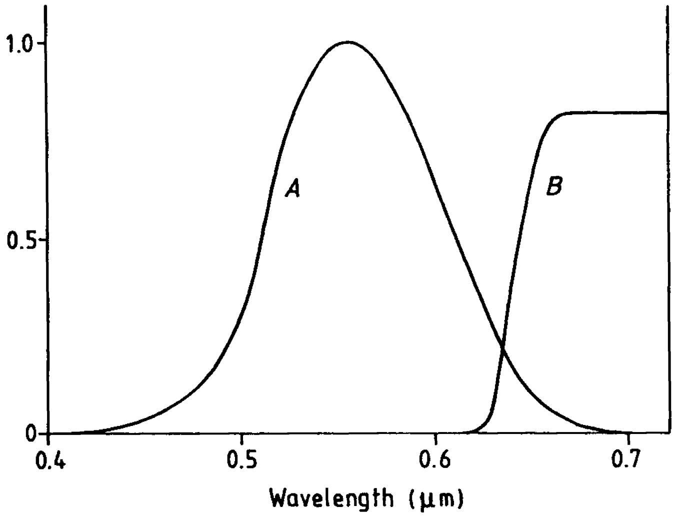

Figure 4 — The visibility function, A, and the transmission of a typical red glass, *B*

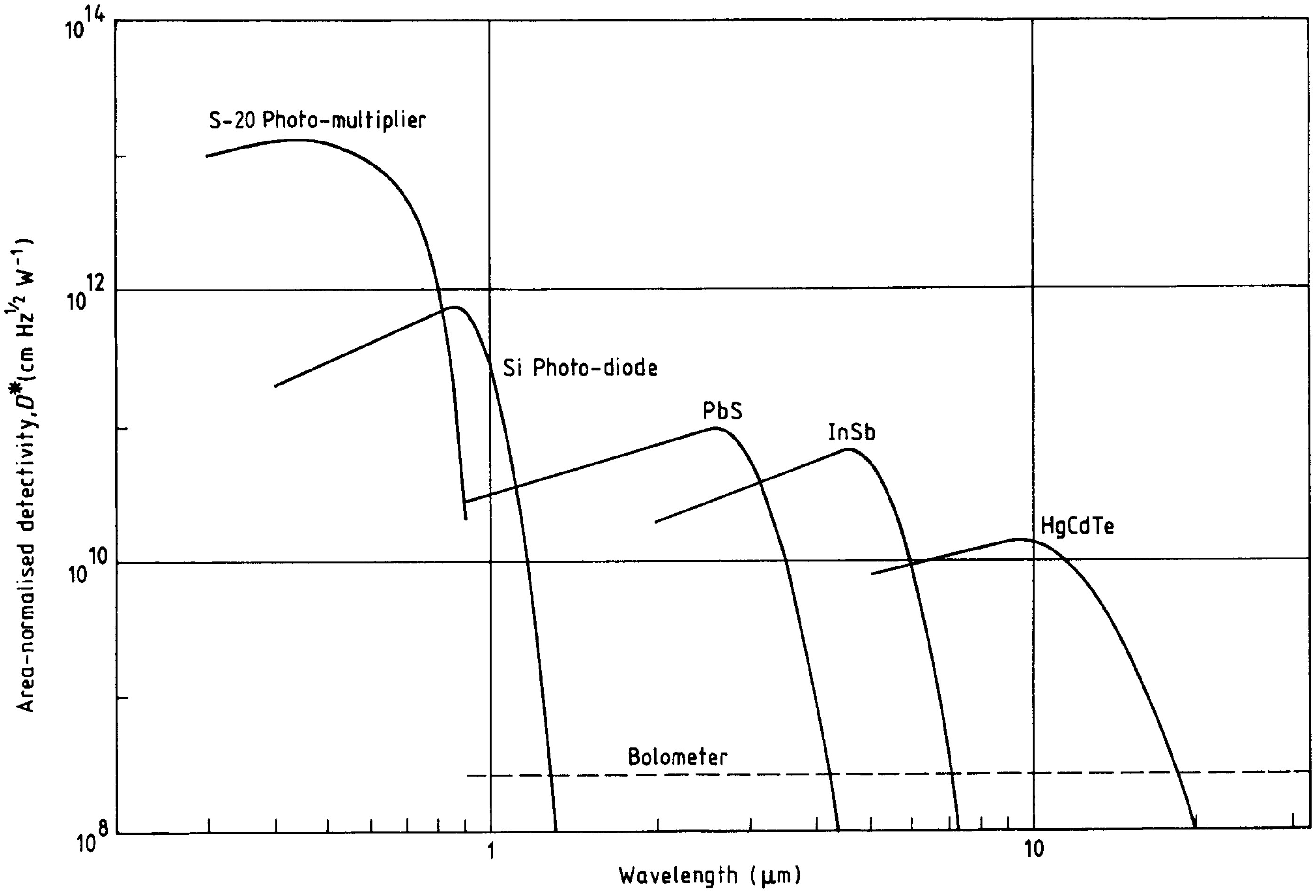

Figure 5 — Relative spectral sensitivities of some photon detectors

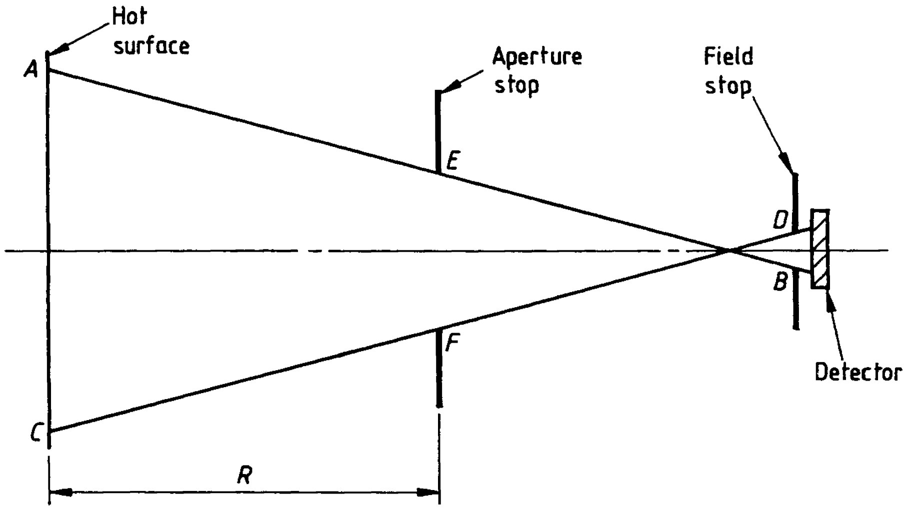

Figure 6 — Diagram of an aperture optical system

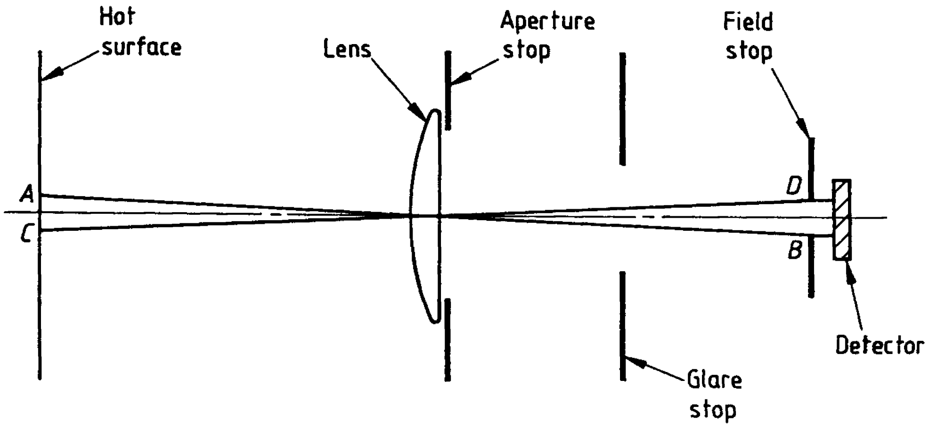

Figure 7 — Diagram of a lens optical system

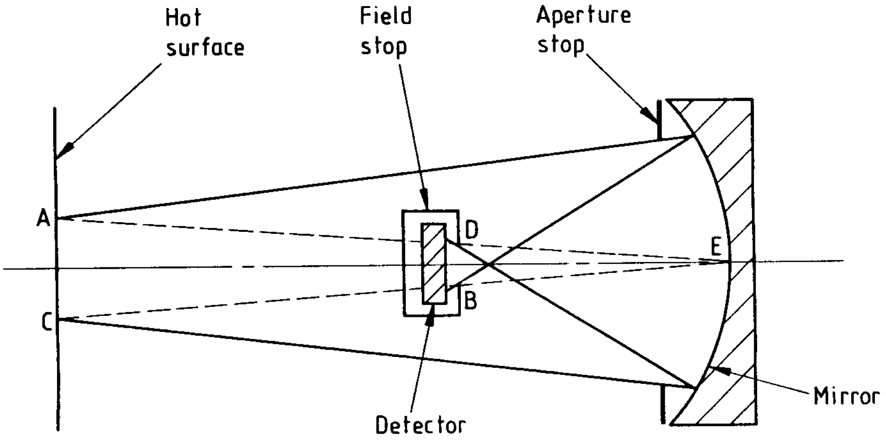

Figure 8 — Diagram of a single mirror optical system

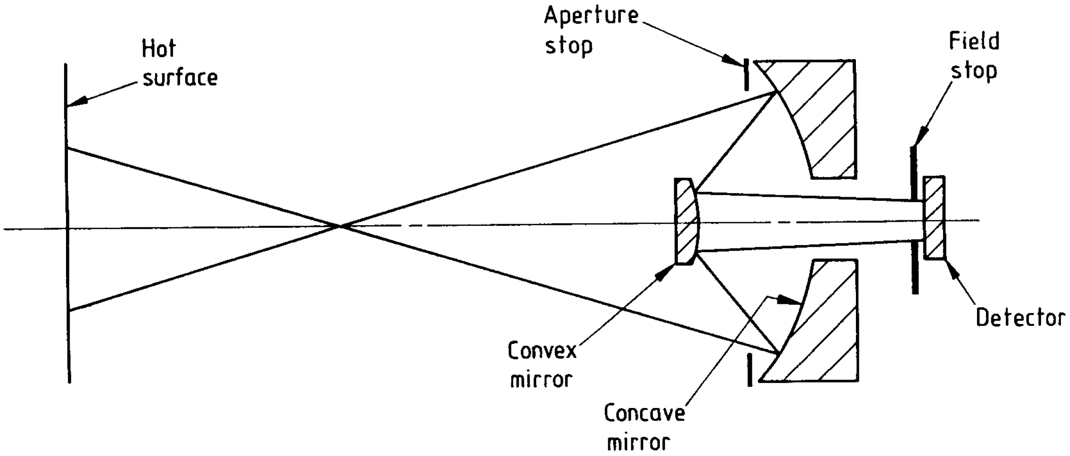

Figure 9 — Diagram of a Cassegrain optical system

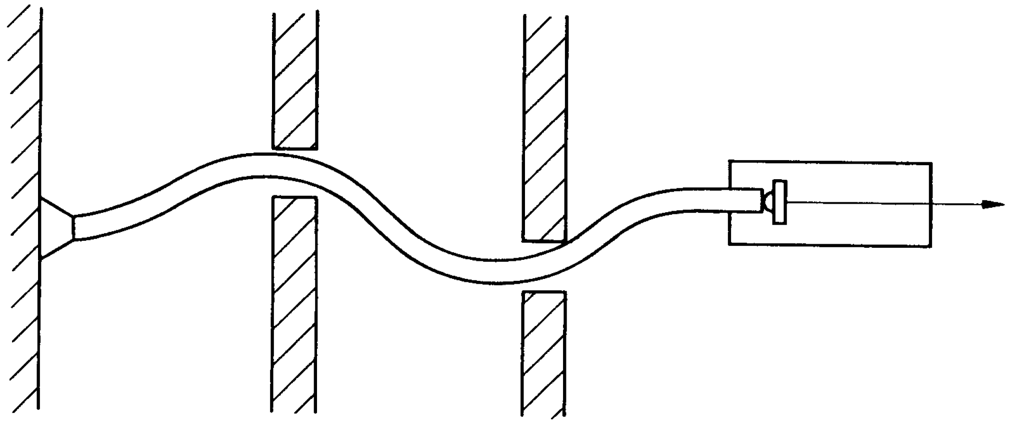

Figure 10 — Fibre optic pyrometer sighted on an inaccessible target

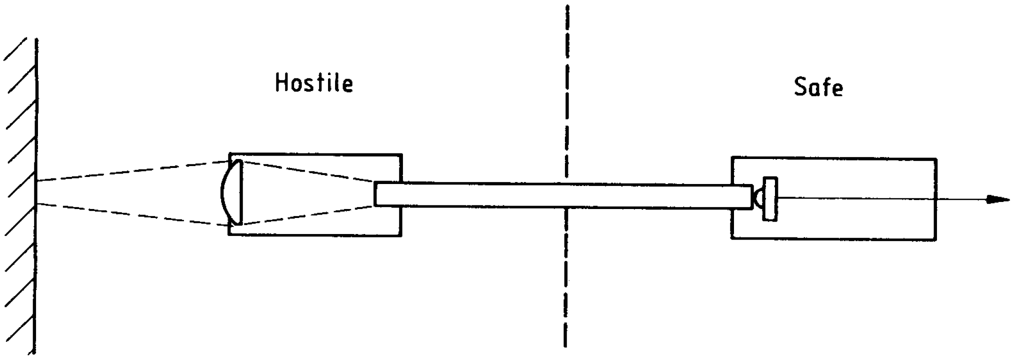

Figure 11 — Fibre optic pyrometer in a hostile environment

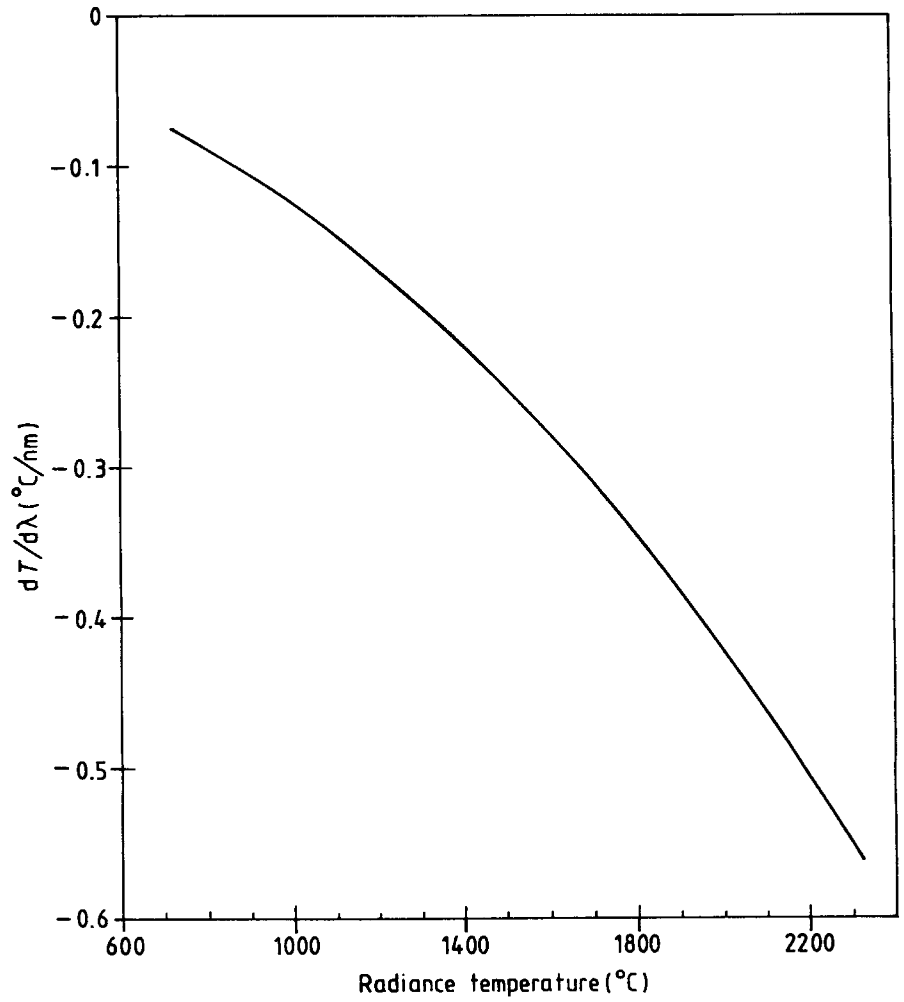

Figure 12 — Corrections for wavelength changes in lamp calibration at 650 nm

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Publications referred to

BS 4727, *Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms.*
BS 4727-4:Group 01, *Radiation and photometry.*
BS 5233, *Glossary of terms used in metrology (incorporating BS 2643).*

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