

Temperature measurement —

Part 5: Guide to selection and use of radiation pyrometers

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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 It is a revision of BS 1041-5:1972 which is withdrawn.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. A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

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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.

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 “Planckian 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.

$$L_\lambda = dL/d\lambda$$

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 $\lambda + d\lambda$, 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 $3.7418 \times 10^{-16} \text{ W m}^2$. 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 $\lambda_{\text{max}} T = 2898 \text{ } \mu\text{m K}$. 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:

$$\epsilon_\lambda L_\lambda(T) + \rho_\lambda L_\lambda(T_s) \quad (7)$$

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:

$$L_\lambda = \epsilon_\lambda L_\lambda(T) + \rho_\lambda L_\lambda(T_s) - L_\lambda(T_o) \quad (8)$$

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

$$L_\lambda = \epsilon_\lambda L_\lambda(T) - L_\lambda(T_o) + (1 - \epsilon_\lambda) L_\lambda(T_s) - L_\lambda(T_o) \quad (9)$$

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:

$$L_\lambda = L_\lambda(T) - L_\lambda(T_o) \quad (10)$$

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:

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

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:

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

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:

$$\frac{1}{\lambda'} = \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \quad (13)$$

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:

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

and

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

Hence

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

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:

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

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:

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

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:

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

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:

$$\ln L_\lambda = A - c_2/\lambda_e T \quad (20)$$

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 hardest 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.