4.9 Radiation and Infrared Pyrometers


Types: (A) Optical (brightness); (B) Ratio (two-color); (C) Total (wide-band) (D) Narrow-band. Note: Fiber-optic designs are covered in Section 4.5.

Applications: Applications are not limited to noncontact high-temperature processes, such as hot metal working, plastic film processing, and glass manufacturing. Infrared is also used in low-temperature applications. These include infrared photographs of accident victims to locate internal bleeding, aerial photographs to detect pollution of water bodies, the detection of the need for crop irrigation, and many others.

Wavelengths Used (Microns): Inexpensive total radiation detectors operate over the range of 0.7 to 8 µm. To penetrate the intervening atmosphere, the 2.2- to 3.8-µm range is used; for applications involving metals, a narrow band around 2.2; for flames, 4.5; for glass, below 8 µm are typical.

Temperature Ranges: −50°F to 6500°F (~−46 to 3600°C) for Spot instruments; 100 to 3500°F (37 to 2000°C) for Line Scanners; 0 to 3500°F (0 to 2000°C) for Thermal Imagers, 1400 to 6300°F (760 to 3500°C) for optical; −40 to 7000°F (~−40 to 4000°C) for narrow-band and total radiation pyrometer designs.

Distance and Target Size: Maximum distance (D) to target is about 100 ft (30 m); minimum target diameter (d) is about 0.05 in (1.5 mm). The field of view of the pyrometer is its D/d ratio and varies from 3:1 to 900:1. Single-wavelength units detect average temperature of field of view; dual-wavelength units detect the hottest part of target within the field of view.

Linearity: Nonlinear, most vary with the 4th power of absolute temperature.

Main Sources of Errors: Variations in the emittance of the target and background; aging of radiation source; background interference; lack of focusing or target is too small to fill the view; radiation absorption by dust, smoke, moisture, atmosphere, or by dirt on the windows.

Methods of Focusing: Most units use lenses to focus on the target. (For alternate methods, refer to the fiber-optic designs in Section 4.5.)

Inaccuracy: Generally from 0.05 to 2% of reading with significant variation due to application details. The error when using designs A and B is generally around 1% of full scale (FS), but on narrow spans can be reduced to 0.5% of reading. (C) is 0.5 to 1% FS, and (D) is 0.25 to 2% FS. Under laboratory conditions, the precision can reach 0.1°C (0.2°F).

Costs: The total range of costs is from $500 to $5,500 with thermal imaging systems up to $60,000. Portable general purpose infrared thermometer units start at around $500 and can reach over $3000 in optical (A) designs. Permanently installed general-purpose, two-wire industrial transmitters start at about $1,500. These can be wide- or narrow-band ([C] and [D]) units. Ratio-type transmitters (B) start at around $4,000. The optical
(A) transmitters cost over $5,000 and are not widely used. When installing pyrometers on a furnace or on boilers, accessories such as cooling jackets, air purge assemblies, safety shutters, and sighting or target tubes are also needed and can more than double the cost of the pyrometer itself. Additional costs involve testing, maintenance, and periodic calibration. When all costs are added up, the total cost is likely to be higher than that of any other thermometer category.

Partial List of Suppliers:
- ABB Inc. Instrumentation (www.abb.com/us/instrumentation)
- Accutech (www.savewithaccutech.com)
- Advanced Control Technology Inc.
- APT Instruments (www.aptinstruments.com)
- Barber-Colman Industrial Instruments (www.barber-colman.com)
- Balluff Inc. (www.balluff.com)
- Chino Works America Inc. (www.america.com)
- CI Systems Inc.
- Concept Engineering
- Dowty Custom ElectronTechnologies (www.citect.com)
- Dickson (www.dicksonweb.com)
- Dwyer Instruments (www.dwyer-inst.com)
- Ecom Instruments Inc. (www.ecom-ex.com)
- Exergen Corp. (www.exergen.com)
- Extech Instruments (www.extech.com)
- Flir Systems Inc. (www.flir.com)
- Flow Research (www.flowresearch.com)
- Fluke Corp. (www.fluke.com)
- Gaumet Process (www.gaumet.com)
- Honeywell Industry Solutions (www.iac.honeywell.com)
- Horiba Instruments Inc. (www.nettune.net/horiba.com)
- Imaging & Sensing Technology (www.istimaging.com)
- Indigo Systems (www.indigosystems.com)
- Instrumentation Group (www.instrumentationgroup.com)
- Ircon Inc. (www.ircon.com)
- Jensen (www.jensentools.com)
- Kobold Instruments, Inc. (www.koboldusa.com)
- L&J Technologies (www.ljtechnologies.com)
- Land Instruments (www.landinst.com)
- Lucent Specialty Fiber Technologies (www.lucent.com/ofis/specialtyfiber)
- Mikron Instrument Co. (www.mikroninst.com)
- Omega/Vanzetti (www.vanzetti.com)
- Pyrometer Instrument Co. (www.pyrometer.com)
- Raytek Inc. (www.raytek.com)
- Rosemount Analytical Inc. (www.processanalytic.com)
- Snell Infrared (www.snellinfrared.com)
- Tel-Tru Manufacturing Co. (www.teltru.com)
- Transcat (www.transcat.com)
- Triplet Corp. (www.triplett.com)
- TTI (www.ttiglobal.com)
- Wahl Instruments Inc. (www.palmerinstruments.com/wahl)
- Watlow Infrared (www.watlow.com)
- Williamson Corp. (www.williamsonir.com)
- Winters Instruments (www.winters.com)
- Yokagawa Corp. of America (www.yca.com)

Note: Most popular are Raytek, Ircon, and Exergen.

An infrared (IR) thermometer is a noncontact radiant energy detector. Every object in the world radiates IR energy. The amount of radiant energy emitted is proportional to the temperature of an object. Noncontact thermometers measure the intensity of the radiant energy and produce a signal proportional to the target temperature.

INTRODUCTION

It was only a few hundred years ago that physicists abandoned the view that heat is a substance and accepted that it is a form of energy that is transferable from one material to another by conduction, convection, or radiation. Since that time it
was discovered that all materials, at all temperatures, down to near absolute zero, radiate electromagnetic energy, which travels at the speed of light (186,000 miles per second). It was also learned that the wavelength at which this radiation occurs depends on the temperature of the material.

The temperature of the material determines both the quantity and the type of energy radiated. As the temperature rises, the wavelength of radiation drops and its frequency rises (Figure 4.9a). For example, at −100°C, the range of radiant energy wavelengths is between 10 and 100 µm, while at 1000°C they are between 1 and 10 µm. As the temperature rises, the dominant form of heat radiation shifts toward the shorter wavelengths: IR (2 to 20 µm), near IR (0.7 to 2 µm), visible (0.4 to 0.7 µm), and UV (0.04 to 0.4 µm). At extremely high temperatures, the hot objects will also radiate x-rays and gamma rays. In industrial applications the bulk of thermal radiation occurs in the IR range, and therefore these thermometers are often referred to as IR thermometers.

This section begins with a discussion of some theoretical aspects of pyrometry, including such topics as emissivity. The description of the specific thermometer designs, features, and installation requirements follows. The section concludes with some definitions of terms used in radiation pyrometry and a list of material for further reading.

THEORETICAL RELATIONSHIPS

Radiation pyrometry stems from Plank’s quantum theory, developed around 1900, and from Stefan-Boltzmann’s law for total radiated energy. According to the Stefan-Boltzmann equation, the total radiant power density emitted (W) by an object is directly related to the emissivity of that object (E) multiplied by a constant (SB) and by the 4th power of absolute temperature (T):

\[
W = (E)(SB)T^4
\]

where

- \( W \) is in W/cm²
- \( E \) is a fraction (unity for a blackbody)
- \( SB \) is the Stefan-Boltzmann constant, having a value of \( 5.6 \times 10^{-8} \text{ W cm}^2\text{K}^4 \)
- \( T \) is absolute temperature of the object in degrees Kelvin

Planck’s law of radiation goes one step beyond Equation 4.9(1) and predicts the level of radiation emitted per unit surface area of a blackbody at each specific wavelength. Planck’s equation is rather complex and therefore is not used much in the everyday work of instrument engineers. According to Planck’s law, the radiation emission peaks at shorter and shorter wavelengths as the temperature rises. This is why one can estimate the temperature of a hot iron in a fire (the shorter the wavelength emitted the whiter and therefore the hotter it is) and why the dotted line connecting the peaks at different temperatures is leaning to the left in Figure 4.9a.

This shift in peak values is expressed by Wien’s law of displacement, relating the wavelength at maximum radiation (\( \lambda_p \)) to absolute temperature (\( T \)) and Wien’s constant (\( C_W \)) as follows:

\[
\lambda_p = C_W / T
\]

Where

- \( \lambda_p \) is in meters
- \( C_W \) is Wien’s constant, having a value of \( 2.898 \times 10^{-3} \text{ mK} \)

FIG. 4.9a
Blackbody radiation is a function of temperature. Dotted line on the left describes a gray body having an emissivity of 0.1. (See definitions at the end of this Section.)
The Theoretical and Real Targets

Only the energy given off between about 0.3 and 20 μm is of sufficient magnitude to be of any consequence. This encompasses the visible spectrum (0.35 to 0.75 μm) and the near IR. The intensity and distribution of this energy from a substance may be compared with that of a blackbody which radiates its energy in a theoretically predictable spectral distribution and intensity, such as that shown for several temperatures in Figure 4.9a. The area under the curve represents the total amount of power radiated at all wavelengths.

Real targets, however, always deviate from an idealized blackbody to some degree. The ratio of energy radiated by a real body to that of a blackbody under similar conditions is termed the emittance (E). Two other optical ratio characteristics of targets are reflectance (R) and transmittance (T) and for a body whose temperature is constant, the sum of E + R + T for any wavelength is always 1.0. The radiation pyrometer would gather the radiation from all three of these energy sources over the wavelength band to which it is sensitive. In Figure 4.9c, if the purpose were to measure the temperature of Object B, and if A were the same temperature as B, B would absorb, emit, reflect, and transmit radiant energy and would appear to be a blackbody.

Frequently A is not uniform in temperature nor does it completely surround B. Furthermore, B might be cooler than A or have a high reflectance which causes it to reflect extraneous sources of radiant energy. If any of these conditions prevail, the measurement of the total energy radiated by B cannot be converted exactly into temperature with the Stefan-Boltzmann law.

For best results, emittance should be high and reflectance low. Transmittance of most solid objects (with the exception of glass) will be near zero. If the process material is not solid, the radiant energy detector will actually see beneath the surface, or if the object is thin, right through it.

Emittance, reflectance, and transmittance are not easy factors to derive and they vary considerably with wavelength. Materials like ferrous metals with a matte surface have a high emittance at the short end of the spectrum, but become lesser emitters for the longer waves. On the other hand, glass acts in nearly the opposite way, being practically transparent to visible energy and almost opaque to wavelengths in the 5- to 7-μm region.

Emittance, Emissivity

The amount of thermal radiation leaving an object depends on the temperature and on the emittance of that object. If the object is a perfect emitter (a blackbody), its emittance is unity. The emissivities of almost all substances are known (Table 4.9d), but unfortunately the emissivity determined under laboratory conditions seldom agrees completely with the actual emittance under actual operating conditions. This is because emissivity is only one component in determining the emittance of an object; other factors (having effects that cannot be found in tables like Table 4.9d) include shape, oxidation, or surface finish. For this reason one is likely to use published emissivity data only when the values are near unity, as is the case for some metal oxides, ceramics, bricks, and glasses.

The uncertainties concerning emittance can be reduced by creating blackbody conditions (target tubes or target holes, which are discussed later) or by using short-wavelength or
Temperature Measurement

The use of short wavelengths is useful because the signal gain is high in this region. This can be seen in Figure 4.9a, where the change in the amount of energy radiated per unit temperature change gets much higher when the wavelength is short. This high output response tends to swamp the effects of emittance variations and makes the performance of the short-wavelength pyrometers acceptable in such applications as iron and steel processes. The high gain of the radiated energy also tends to swamp the absorption effects of steam, dust, or water spray.

The ratio, or two-color, pyrometer overcomes emittance uncertainties, but has other limitations, which will be discussed later. The emissivities of most materials, including metals, vary a great deal, and some emissivities also vary with temperature. When this is the case, the ratio thermometer is also disabled and the only solution is the actual, on-line measurement of emissivity (using laser devices, which are discussed later). The general rule is to measure the temperature of an object in a location where its emissivity is the highest and/or where the change in radiated energy is more sensitive to temperature changes than to changes in emissivity.

**SELECTING THE RADIATION PYROMETER**

In selecting the appropriate type of radiation pyrometer to be used in detecting the temperature of a particular process, one would prefer to select a wavelength-band in which the transmittance \( T \) is near zero (the material is opaque). In addition, one would like to select a wavelength-band that will not be absorbed by the atmosphere the radiation has to pass through. These two considerations result in a requirement for matching the pyrometer wavelength to the particular process.

### TABLE 4.9d

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity</th>
<th>Material</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td></td>
<td>Iron</td>
<td></td>
</tr>
<tr>
<td>Unoxidized</td>
<td>0.06</td>
<td>Oxidized</td>
<td>0.89</td>
</tr>
<tr>
<td>Oxidized</td>
<td>0.19</td>
<td>Rusted</td>
<td>0.65</td>
</tr>
<tr>
<td>Brass (oxidized)</td>
<td>0.60</td>
<td>Lead (oxidized)</td>
<td>0.63</td>
</tr>
<tr>
<td>Calorized Copper</td>
<td>0.26</td>
<td>Monel (oxidized)</td>
<td>0.43</td>
</tr>
<tr>
<td>Calorized Copper</td>
<td>0.19</td>
<td>Nickel</td>
<td>0.12</td>
</tr>
<tr>
<td>(oxidized)</td>
<td></td>
<td>Bright</td>
<td>0.12</td>
</tr>
<tr>
<td>Calorized Steel</td>
<td>0.57</td>
<td>Oxidized</td>
<td>0.85</td>
</tr>
<tr>
<td>(oxidized)</td>
<td></td>
<td>Silica Brick</td>
<td>0.85</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.79</td>
<td>Silver (unoxidized)</td>
<td>0.03</td>
</tr>
<tr>
<td>Cast Iron</td>
<td></td>
<td>Steel (oxidized)</td>
<td>0.79</td>
</tr>
<tr>
<td>Oxidized</td>
<td>0.79</td>
<td>Steel Plate (rough)</td>
<td>0.97</td>
</tr>
<tr>
<td>Strongly oxidized</td>
<td>0.95</td>
<td>Tungsten (unoxidized)</td>
<td>0.07</td>
</tr>
<tr>
<td>Copper (oxidized)</td>
<td>0.60</td>
<td>Wrought Iron</td>
<td>0.94</td>
</tr>
<tr>
<td>Fire Brick</td>
<td>0.75</td>
<td>(dull oxidized)</td>
<td>0.94</td>
</tr>
<tr>
<td>Gold</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.9e illustrates three different processes showing both the atmospheric absorption bands and the transmittance curves of the particular process materials. The arrow with the letter P for pyrometer indicates the appropriate wavelength-band selection for the radiation thermometer for each process. For polyethylene it is around 3.4 \( \mu m \), for glass 5 \( \mu m \), and for polyester 8 \( \mu m \).

Because of the different needs of the various processes, each radiation pyrometer manufacturer has developed a range of products operating in a variety of wavelength bands as shown in Figure 4.1j and Figure 4.9f. Of the eight bands shown on this illustration, #6 can be considered for use on a polyethylene and #8 on a glass temperature measurement applications. (If the glass is thick enough it can appear opaque even in the near-infrared range.)
Short wavelength units like #1, #2, and #3 can be used in iron and steel processing. Long or broad wavelength pyrometers (#7) are useful at lower temperatures where short wavelength radiation can be undetectable. Materials like glass are transparent to shorter wavelengths (Figure 4.9e). Therefore, shortwave pyrometers would not detect the surface temperature, but would measure the temperature below the surface. In some processes, like lamp sealing, this is actually desirable, and therefore the 3- to 4-µm band is used.

**RADIATION PYROMETER DESIGNS**

Pyrometers can be portable or permanently installed; the radiated energy can reach them through focusing on lenses or through optical fibers. In addition, they can be categorized according to the number and width of the wavelength-bands used. When the full spectrum of 0.3 to 15 µm is utilized (#5 on Figure 4.9f), the device is called a wide-band or total radiation pyrometer. When a single small segment of the spectrum is used (for example, #8 on Figure 4.9f), the design is called a narrow-band pyrometer. If that narrow band falls within the visible spectrum (#1 on Figure 4.9f), this subgroup of the narrow-band pyrometers is called an optical, color, or brightness pyrometer.

When, instead of measuring the radiation intensity of a single wavelength band, the instrument detects the ratio of the intensities of two wavelengths, the pyrometer is called a ratio, or two-color, thermometer (Figure 4.9g). When a pyrometer operates in the IR spectrum (0.7 to about 15 µm), sometimes the unit is referred to as an IR thermometer.

Of these many design variations, the fiber-optic units will not be discussed here. Section 4.5 is devoted to their description and they are also covered in Section 4.1 (Figure 4.1n). The others are discussed below.

With the passage of time, the use of total radiation pyrometers has dropped and the use of the more accurate (and more expensive) ratio pyrometers has increased. Optical pyrometers are most often used as portable units.

**Figure 4.9f**

Pyrometers and their wavelength-bands.

**Figure 4.9g**

Ratio pyrometer used to detect the temperatures of molten metals, kilns, and furnaces. (Courtesy of Ircon Inc.)

**Figure 4.9h**

Error in reading of broad-band radiation pyrometer as function of temperature and emissivity.

**Total Radiation Pyrometers**

Broadband (total) radiation pyrometers attempt to measure as much of the radiant energy coming from a hot body as possible. The simplest of the three types (total, narrow, ratio), it has substantially no selectivity for specific wavelengths other than a cutoff inherent in the optical system and is dependent on the total emittance of the surface being measured.

Figure 4.9h shows the error in reading for various emissivities and temperatures when a typical instrument of this type is calibrated to read blackbody temperatures. A calibration control on the readout instrument permits the user to compensate for this error, which corrects the reading as long as the emittance does not change. The proper setting of the adjustment is made with the aid of a second thermometer known to be correct; or, knowing the nature of the target and referring to a table giving total emissivities (see Table 4.9d), the adjustment can be set to the correct figure.
Broadband radiation pyrometers must have an unobstructed sighting path to the target. The presence of smoke or carbon dioxide will absorb some of the radiant energy and cause a low reading. The optical system must be kept clean, with a sighting window protected from any corrosive gases that otherwise would come in contact with it. In furnaces, a closed-end sighting tube is frequently used to protect the optics and to provide a clear sighting path (Figure 4.9i). The back end of the tube assumes the same temperature as the furnace. Water or air cooling is sometimes used to keep the housing temperature cool on these installations.

Ambient temperature compensation is required for those total radiation pyrometers using a thermopile detector. Nickel wire, having a temperature coefficient opposite to that of the thermopile wires, is most often utilized. For low-temperature work, a thermostatically controlled housing is often employed to eliminate any ambient temperature fluctuations.

**Narrow-Band Pyrometers**

Single-band pass (narrow-band) pyrometers operate over a selected, usually narrow, band of the energy spectrum centered at a desired point. For high-temperature measurement of metals, for instance, the band might be very narrow at the 0.65-µm point, the read end of the visible spectrum where metal emissivity is highest. At this visible point, the instrument might be referred to as a brightness pyrometer.

To measure gas temperatures, a band around 4.3 µm to pick up carbon dioxide might be chosen, while glass surface temperatures, previously mentioned, would be measured in the 5- to 7-µm wavelength.

Emissivity over a narrow wavelength band will not vary as much as it would over the total spectrum, but the limited-band pyrometer will suffer somewhat from a lack of sensitivity because of the reduced energy available. The use of more sensitive photon detectors helps make up this deficiency and also provides a desired band pass. Because the energy content of the radiation increases as the wavelength gets shorter, the narrower bands are most often used to detect higher temperatures (above 500°C, or 932°F). A narrow band is usually less than 0.5 µm wide.

**Ratio Pyrometers**

The ratio, or two-color, pyrometer measures the energy it receives from two rather narrow bands and divides one by the other. When the two bands are chosen so that there is very little change in emissivity from one to the other, such as would be the case if the bands were close together (Figure 4.9g), the emissivity factor nearly cancels out. Thus, low emissivity bodies, which create the most error for the broadband single-band pyrometers, do not have such a large effect on the ratio-type instrument.

The selection of the two wavelengths is not arbitrary but, like the single-band pyrometers, is made for the particular application.

Ratio pyrometers are more complex and more expensive than single-band pyrometers, but they provide better accuracies when the target behaves like a gray object or when its emissivity is a variable. (The emissivity of many substances varies with temperature.) In addition to being independent of emissivity, measurements made by ratio pyrometers are also unaffected by dust or other contaminants in the field of view (such as dirty windows), by changes in target size, or by periodic blockage of the sight path.

In some more advanced designs, more than two colors (wavelengths) are used and their evaluation algorithm is more complex than a simple ratio.

Figure 4.9j illustrates the operation of the ratio (two-color) pyrometer where the wavelengths are alternatively selected by a rotating filter wheel. These eliminate emittance errors if the emittance is the same at both wavelengths. Unfortunately this is seldom the case; usually emittance is wavelength-dependent. The only solution is to bring the two wavelengths very close together, but then they become insensitive to temperature.
For these reasons the ratio pyrometers are not as widely used as one might expect. On the other hand, they are still very useful on applications where the target is too small to fill the field or view (e.g., in the drawing and coating of wires) or where the target is obscured by cool dust (as in cement kilns).

**Manual Optical Pyrometers**

Optical pyrometers are narrow-band or two-color radiation pyrometers that operate in the visible spectrum around the 0.65-µm point. The human eye, acting as the detector in the manually balanced type, compares a source of known radiant energy generated within the instrument by a calibrated tungsten lamp to the incoming unknown source. A filter interposed between the eye and both sources of energy cuts out the shorter wavelengths. This serves a dual purpose: (1) it minimizes the difference between eyes, permitting an easier color match, and (2) it permits an extension of the temperature range beyond the point where the eye could no longer tolerate the amount of energy if viewed directly (Figure 4.9k).

The instrument is shaped to be held in the hand and up to the eye so that it may be sighted on the target. An adjustable focus permits the operator to focus an image of the source whose temperature is to be determined. The filament of the standard source is placed on the same plane as this image so that the two appear superimposed on one another when viewed through the eyepiece.

A null type of balance is usually used where a rheostat, moving against a calibrated dial, is manually rotated to vary the current through the standard source until it just disappears into the field of the unknown. A slight modification of this principle maintains the standard source constant and varies the amount of interposing absorbing gate opening in the optical path.

The range of the manual optical pyrometer is limited on the low end to a minimum of 1400°F (760°C), since there is insufficient emission of visible light for an accurate comparison below this figure. At 2400°F (1316°C), the image would become too bright to look at directly, but filters are usually interposed to permit readings as high as 6300°F (3500°C).

The use of the human eye as the detector restricts accuracy somewhat. This is because the eye responds to both color and brightness rather than directly to energy and no two eyes are alike. However, it is possible to detect both a color and a brightness match by adjusting to the minimum difference between known and unknown.

The manual optical pyrometer is a self-contained unit with its own power supply for operating the current for the known radiant energy source. It can be mounted in place or handheld by an operator as he takes a sighting. Figure 4.9l and Figure 4.11 illustrate the relationship between distance and target size in using portable IR pyrometers.

Its advantages include that it is a light, portable, and self-contained unit of reasonable accuracy if sighted into a near-blackbody furnace. Its disadvantages are:

1. It requires the operator to adjust the temperature dial manually. It is not suitable for alarm or control functions.
2. It can only be used at relatively high temperatures where plenty of visible energy is given off.
3. It is subject to emissivity errors inherent to a narrow-band radiation pyrometer.

**FIG. 4.9k**

In optical pyrometers the target radiation is focused on a lamp and is compared to the radiation intensity of the light filament. Matching of the two intensities is determined visually by either adjusting the current flow through the calibrated tungsten lamp (left) or by changing the opening of a sliding gate (right) until the two intensities are balanced. The use of a red filter allows the comparison to be made at a specific color (wavelength).

**FIG. 4.9l**

Target areas and distances applicable to portable infrared pyrometers. (Courtesy of Wahl Instruments Inc.)
Automatic Optical and IR Pyrometers

The automatic optical pyrometer uses an electrical radiation detector rather than the human eye, and consequently it is not limited to the visible wavelengths of the spectrum. It can reach far into the IR or the near UV using a narrow band, a two-color band, or a wide band selection in accordance with the optical system and detector.

Although there are many adaptations, the automatic optical and/or IR pyrometer operates essentially by comparing the amount of radiation emitted by the target with that emitted by an internally controlled reference source. The output is proportional to the difference in radiation between the variable source and the fixed reference. The system usually consists of two components: the optical head and the electronic amplifier.

In some models (Figure 4.9m), the optical head contains a temperature-controlled blackbody source, the required filters, a detector, a preamplifier, and an optical chopper. The chopper, driven by a synchronous motor, alternately exposes the detector to incoming and cavity radiations at a frequency that might be in the 60- to 120-cps range.

Another model (Figure 4.9n) uses the human eye to adjust the focus. Radiant energy passes through the front lens onto a dichroic mirror, which allows visible light to pass through, while IR radiation is reflected onto the detector. The operator adjusts the eyepiece for the correct focus by just filling the circle reticle plate with the visible image.

The calibrate flag is solenoid-operated from the amplifier. When actuated, it cuts off the radiation coming through the lens and focuses the calibrate lamp onto the detector. The known radiation from the lamp allows the entire system to be checked.

Automatic optical or IR pyrometers are closely tied in with radiometers and other optical devices. Telescopic lenses are sometimes employed for their special effects. The instrument may have a wide-angle field of view for large area scanning or it may have a very narrow angle where the target is only 0.05 in. (1.27 mm) in diameter at 8 in. (203 mm) distance.

The entire pyrometer, optics plus amplifier, has been packaged into a single, handheld, and battery-operated device for open fieldwork. It is shaped somewhat like a pistol held in the hand and aimed at the target. Pulling the trigger (Figure 4.9l) energizes the standard reference source and the readout indicator.

A very practical application of the IR pyrometer is to use it in the 8- to 14-µm range as a hot spot detector. The operator can move quickly from one object to another looking for undesirable internal sources of heat generation. It is possible to attach a camera to the unit and take a temperature profile as a picture for immediate or future analysis.

Table 4.9o lists some applications at various spectral responses for this versatile temperature-measuring device.

### DETECTORS

The detector receives the radiant energy focused on it by the optical system and generates an electric output signal in response to it. Detectors are grouped into two main classes: thermal detectors and photo-detectors.

#### Thermal Detectors

Thermal detectors generate an output because they are heated by the energy they absorb. This category includes thermocouples (TCs), thermopiles, pneumatic detectors, the metallic...
or the thermistor-type bolometers, and the pyroelectric devices. Relative to the photo-detectors, these units have a lower sensitivity, and their output are less affected by changes in the radiated wavelengths. Most are limited in their speeds of response by their mass; others, like the pyroelectric detectors, are rate-sensitive. This means that the output responds not to the temperature of the sensor, but to the rate at which it is changing. While this speeds up the response, it also requires more electronics and complexity. The use of pyroelectric detectors is limited by their need for optical shopping and their sensitivity to vibration.

Advanced thin-film thermopiles achieve response times in the 10- to 15-ms range, while silicon thermopiles also increase the output signal strength. Thermopiles and bolometers respond to radiant energy throughout the whole spectrum and therefore are more suited for detection in total radiation pyrometers. Considering speed, sensitivity, and stability, the best choice for total-radiation applications is the silicon thermopile detector.

**Photo-Detectors**

Photo-detectors are wavelength-sensitive and therefore are better suited to narrow-band pyrometry. The output produced by the photo-multiplier tubes and photo-detectors is not caused by heat, but by the electrical charges that are released as the radiant energy reaches the detector. The sensitivities of these detectors are in the microseconds. Their main disadvantage is instability at longer wavelengths and when operating at higher temperatures. Consequently, they are used as narrow-band detectors on short-wavelength applications and are frequently provided with cooling.

Photo-detectors can be photo-conductive, photo-voltaic, or photo-emissive devices (Figure 4.9p). The use of photo-emissive devices, such as photo-multiplier tubes, has been diminishing. Photo-conductive detectors change their resistance as a function of temperature and include the lead selenide and lead sulfide cells. They are sensitive in the 1- to 3-µm range and therefore are either used with filters (Figures 4.9k, 4.9m, and 4.9n) in narrow-band pyrometers or in medium temperature (200 to 800°F, or 93 to 427°C) measurement (Figure 4.9a) applications as wideband detectors.

The photo-voltaic cell’s output is a function of the absorbed radiation. The most widely used cell material is silicone, but germanium and iridium antimonide are also used. The silicon cell matches the short-wavelength thermal emissions of high-temperature objects (0.5 to 1.0 µm) at temperatures from 750 to 7000°F (400 to 3870°C). The germanium cell with its 0.7- to 1.8-µm range is suited for medium temperature measurement and is more stable, more reproducible, and faster than the photo-conductive lead sulfide cells.

Iridium antimonide has been used to detect the temperature of hot glass surfaces, but due to its poor sensitivity it has been replaced in many applications with pyroelectric thermal detectors in the 8- to 14-µm range. The speed of the photo-detectors also permits them to be used for measuring the temperature of small objects moving at high speed, where relative energy output would be small.

**SELECTION**

In selecting a radiation pyrometer for a particular application, consideration must be given to the following:

1. The field of view, or the size-distance relationship
2. The transmission qualities of the collector system and any windows or filters in the optical path.
3. The band pass sensitivity of the detector

Figure 4.9q shows a typical wide-angle field of view. Note how the target size requirement necks down to a minimum at the focal length of lens in such a system. The narrow-angle field of view, shown in Figure 4.9r, flares out more slowly. Cross-sectional areas in either case can vary from circular to rectangular and even slot-shaped, depending on apertures in the housing design. On some designs telescopic eyepieces can magnify the radiant energy so that much smaller targets at greater distances can be viewed. Targets 1/16 in.
Temperature Measurement

(1.6 mm) in diameter are feasible with the proper pyrometer design.

The physical shape of the optical system (lens of curved mirrors) and its mounting within the pyrometer housing control the sighting path, while the material from which it is made determines the optical properties. Glass does not transmit well beyond 2.5 \( \mu \text{m} \) and is suitable only for the higher temperatures where plenty of output is available. Other popular optical materials are quartz (fused silica) to 4 \( \mu \text{m} \) and crystalline calcium fluoride to about 10 \( \mu \text{m} \). Lesser used (and more expensive) materials will increase the transmission even more.

Windows and filters in front of or behind the optical system can alter the transmission properties greatly. A plate glass window in front of a calcium fluoride lens, for instance, will very effectively stop the longer wavelengths which would have passed through the lens. A band pass filter might be purposely placed in front of the detector to cut off unwanted wavelengths.

**INSTALLATIONS AND ACCESSORIES**

The installation of an IR thermometer requires attention to detail to ensure successful operation. Figure 4.11 has illustrated some of the problems with installation of IR thermometers. Ideally, a clear unobstructed line of sight is required and the target has to be large enough to fill the cone of vision. The spot size required is related to the distance to the sensor and the user should consult the manual for details.

Solid obstructions have to be removed or eliminated from the field of view by possibly aiming the instrument at a different angle or by using a fiber optic remote sensor system. For applications with sighting windows, the instrument must be selected to use a wavelength that will pass through the window material unchanged. The window also must be large enough so as not to obstruct the cone of vision, and it has to be kept clean by possibly using an air purge. Smoke, steam, and dust all cause temperature fluctuations.

The temperature-measuring requirement for industrial applications involves either the surface temperature of equipment or objects that are out in the open or the temperature inside vessels, pipes, and furnaces. Surface-temperature-sensing pyrometers can be portable (Figure 4.9l) or permanently installed. When internal temperatures are of interest, one can look into the process through windows (Figure 4.9s). In such installations, the pyrometer can be mounted on an adjacent pedestal or supported by a bracket attached to the vessel, as long as the pyrometer is shielded from excessive heat. It is advisable to provide an internal purge to periodically clear the dirt that is likely to accumulate on the window.

When a pyrometer is installed through the wall of a furnace a large number of installation-related accessory components are needed. These can easily double the basic cost of the pyrometer itself. In Figure 4.9i, the pyrometer sensor head and its aiming tube, or telescope, are mounted inside the cooling jacket. The coolant flow required is a function of the ambient temperature in the area and varies from 0.2 GPH (0.8 1ph) at 150°F (60°C) all the way up to 20 GPH (76 1ph) at 600°F (315°C). Proceeding to the left on Figure 4.9i, the next component is the air purge assembly followed by the safety shutter, or slide gate shutter, which allows the sealing of the furnace when the pyrometer is removed.

Sighting the pyrometer on the target through a tube purged by a clean and nonabsorbing gas minimizes the need for cleaning the lenses and windows. When interference from flames or other sources cannot be filtered out optically, the purged sighting tube, shown on the left of Figure 4.9i, can be extended almost to the target. In this way the sighting tube allows a more accurate targeting on the point of interest and also makes purging more effective as the air fills the tube.

**FIG. 4.9r**
Sighting path of the narrow-angle total radiation pyrometer.

**FIG. 4.9s**
Radiation pyrometer installed on a combustion process. (Courtesy of Williamson Corp.)
This also reduces the influence of smoke and dust in the atmosphere between the sensing head and the desired target and reduces unwanted background radiation. Sighting tubes are available in different lengths and in constructions of Inconel (for up to 2100°F, or 1105°C), silicon carbide (up to 3000°F, or 1650°C), refractory alumina (up to 2900°F, or 1600°C), or aluminum or stainless steel (below 600°F, or 315°C).

Closed-end target tubes (also shown in Figure 4.9i) are also made of the above listed materials and are used on liquid service or in other processes where the inside temperature of the target tube sufficiently represents the process temperature. In addition to sighting tubes or in place of target tubes, it is possible to form the object of interest into a better or ideal emitter. This is done by forming the object into a concave shape or drilling a hole in the target and sighting the pyrometer onto that hole.

**ADVANCES AND NEW DEVELOPMENTS**

New technologies such as microprocessors, fiber optics, lasers, buses, and networks have also changed radiation pyrometry. One important new development is the availability of the laser reflectometer (Pyrolaser is a trademark of Pyrometer Instrument Co.) which can measure the emissivity of the process material at the same location, temperature, and wavelength as used in the pyrometer. This eliminates the potential for emissivity error by allowing its value to be continuously and automatically corrected. This device also helps in overcoming errors caused by radiation from hotter surfaces.

This is done by taking a radiant measurement of the hotter refractory surface and compensating for it by calculating its reflectivity as: \( R = 1 - \varepsilon \). As of this writing, the laser-based emissivity compensator operates at only one wavelength (0.865 µm) and therefore is effective only if that is the wavelength of interest. However, it is likely that with the passage of time it will become available at other wavelengths also.

Other advances include the increase in the number of spectral bands available, the reduction in the required target size (1 mm diameter), and the increase in the distance-to-target ratios, which can exceed 200:1. The intelligent pyrometer is more than a sensor—it is a measurement system that routinely provides linear outputs and digital displays and can minimize ambient effects. Intelligent units using two pyrometers are also used to correct for background radiation.

Another area of technological innovation has been in the field of line-scanning pyrometers. These have been developed to monitor the surface temperatures of cement kilns to indicate internal material buildup or refractory deterioration. As the pyrometer scans left to right while the kiln rotates on its horizontal axis, the pyrometer scans its total surface and feeds this information into a small computer for processing. By the same technique, moving sheets of paper, glass, steel, or plastic can be scanned.

There is a growing market for line scanners that can produce a two-dimensional thermal image. This type of IR thermometer is used to measure wide webs such as hot strip steel, glass, plastic, and paper. This instrument utilizes one detector and two 45-degree mirrors with one mirror rotating and scanning over a 90° angle as shown in Figure 4.10. For moving targets, the instrument uses a software technique to create two-dimensional thermal images of the moving web. The software provides temperatures at any location on the web and can provide output signals that can be used for closed loop control or stored for future review.

Thermal imagery is a rapidly growing application of IR technology that is used on some automobiles and by military and law enforcement in night vision applications. Architectural analysis of building insulation, surveillance, and quality control are other uses. This imaging system is an IR thermometer that uses a detector called a focal plane array instead of a single sensor. Its functionality is similar to a digital camera, except that, instead of capturing photographic images, each pixel measures temperature. A two-dimensional image is created using software resident within the system. The detector can have as many as 76,000 pixels. The image of the temperature profile can be used for closed loop control of processes, such as detecting defective personal computer boards, or stored away for future analysis.

**SUMMARY**

Most manufacturers of IR instruments continue to refine existing products and offer enhanced capability with newer models. One new model offers bidirectional digital networking communications. Multiple sensors can connect to host systems for monitoring, control, and diagnostics. The design engineer is strongly urged to consult with multiple vendors to get recommendations for selecting the proper instrument for each application.

The broadband pyrometer is used generally in industry for readout and automatic control. It can cover wide temperature ranges and is the least expensive of the three types. Narrow-band and two-color pyrometers are used, where necessary, to minimize the emissivity effects and for special applications where it is desirable to select the particular band pass.

The prospective user of a radiation pyrometer should consider the following points:

1. Target temperature, low, normal, and high limits.
3. Target material and emittance.
5. Is target stationary or moving? If moving, will the speed of response of the pyrometer be fast enough?
6. Atmospheric conditions between target and detector.
7. Ambient temperature.

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8. Can pyrometer sight directly on target or must it sight through a sealed auxiliary window such as required for vacuum or pressure?

9. Is scale to be read directly in temperature units or will an arbitrary reading be satisfactory?

**Advantages**

IR thermometers are ideal for moving targets such as glass, plastic, and steel. They do not interfere with the process. They are also ideal for measuring products with very high temperatures or hostile environments. They can see through windows to measure products in a vacuum furnace or a semiconductor reactor. Infrared thermometers can measure targets as small as 0.025 in. in diameter and can respond in 10 ms to a temperature change. Other advantages of IR thermometers include:

1. They do not require physical contact with material whose temperature is being measured.
2. They have a fast speed of response—they can be used on moving targets.
3. They can look at small targets (1/16 in. or 1.6 mm in diameter) or measure the average temperature over a wide area.
4. They measure much higher temperatures than TCs.

**Disadvantages**

The disadvantages of IR thermometers include:

1. They are more fragile and costlier than TCs, resistance temperature detector, or thermistors.
2. They have a nonlinear scale shape, approximating the 4th power of the temperature.
3. Their emissivity of target may cause a low temperature reading if not corrected.
4. A relatively wide temperature span is required.

**DEFINITIONS**

**Absorbance (A)**—Ratio of radiant energy absorbed by a body to the corresponding absorption of a blackbody at the same temperature. Absorbance equals emittance on bodies whose temperature is not changing. 

\[ A = 1 - R - T \]  

where \( R \) is the reflectance and \( T \) is the transmittance.

**Band pass filter**—An optical or detector filter that permits the passage of a narrow band of the total spectrum. It excludes or is opaque to all other wavelengths.

**Blackbody**—The perfect absorber of all radiant energy that strikes it. The blackbody is also a perfect emitter. Therefore, both its absorbance (\( A \)) and emissivity (\( E \)) are unity. The blackbody radiates energy in predictable spectral distributions and intensities which are a function of the blackbody’s absolute temperature.

**Bolometer**—Thermal detector that changes its electrical resistance as a function of the radiant energy striking it.

**Brightness pyrometer**—Uses the radiant energy on each side of a fixed wavelength of the spectrum. This band is quite narrow and usually centered at 0.65 \( \mu \text{m} \) in the orange-red area of the visible spectrum.

**Detector**—A device that measures the amount of energy radiated by an object. It can be a thermal detector or a photodetector. Thermal detectors respond to radiation by changing their volume, capacitance, or generation of millivolts; they can be TCs, thermopiles, pneumatic detectors, or bolometers. Their common feature is their relatively slow response. Photodetectors are semiconductors that produce a signal in proportion to the photon flux that strikes them.

**Emissivity or emittance (E)**—The ratio of radiant energy emitted by an object divided by the radiant energy which a blackbody would emit at that same temperature. If the emittance is the same at all wavelengths, the object is called a gray body. Some industrial materials change their emissivity with temperature and sometimes with other variables also. Emissivity always equals absorption and it also equals 1 minus the sum of reflectance and transmittance \( (E = A = 1 - T - R) \).

**Gray body**—An object having an emittance of less than unity, but this emittance is constant at all wavelengths (over that part of the spectrum where the measurement takes place). This means that gray-body radiation curves are identical to the ones shown in Figure 4.9a, except that they are dropped down on the radiated power density scale.

**Infrared**—That portion of the spectrum whose wavelength is longer than that of red light. Only the portion between 0.7 and 20 \( \mu \text{m} \) gives usable energy for radiation detectors.

**Mechanical emissivity enhancement**—Mechanically increasing the emissivity of a surface to near-blackbody conditions (using multiple reflection).

**Micron**—0.001 mm. 10,000 Å. A unit used to measure wavelengths of radiant energy.

**Narrow-band pyrometer**—A radiation pyrometer that is sensitive to only a narrow segment of wavelengths.
within the total radiation spectrum. Optical pyrometers are one of the devices in this category.

**Optical pyrometer**—Also called a brightness pyrometer, it uses a narrow band of radiation within the visible range (0.4 to 0.7 μm) to measure temperature by color matching and other techniques.

**Photodetector**—Measures thermal radiation by producing an output through release of electrical changes within its body. They are small flakes of crystalline materials such as CdS or InSb which respond to different portions of the spectrum, consequently showing great selectivity in the wavelengths at which they operate.

**Ratio pyrometer**—See two-color pyrometer.

**Reflectance or reflectivity (R)**—The percentage of the total radiation falling on a body which is directly reflected without entry. Reflectance is zero for a blackbody, and nearly 100 percent for highly polished surface. \( R = 1 - A - T \), where \( A \) is the absorbance and \( T \) is the transmissivity.)

**Spectral emissivity**—The ratio of emittance at a specific wavelength or very narrow band to that of a blackbody at same temperature.

**Thermopile**—Measures thermal radiation by absorption to become hotter than its surroundings. It is a number of small TCs arranged like the spokes of a wheel with the hot junction at the hub. The TCs are connected in series and the output is based on the difference between the hot and cold junctions.

**Total emissivity**—The ratio of the integrated value of all spectral emittances to that of a blackbody.

**Transmittance or transmissivity (T)**—The percentage of the total radiant energy falling on a body, which passes directly through it without being absorbed. Transmittance is zero for a blackbody and nearly 100 percent for a material like glass in the visible spectrum region. \( T = 1 - A - R \), where \( A \) is the absorbance and \( R \) is the reflectance.)

**Two-color pyrometer**—Measures temperature as a function of the radiation ratio emitted around two narrow wavelength bands. Also called ratio pyrometer.

**Wideband (total) pyrometer**—A radiation thermometer that measures the total power density emitted by the material of interest over a wide range of wavelengths.

## Reference


## Bibliography


