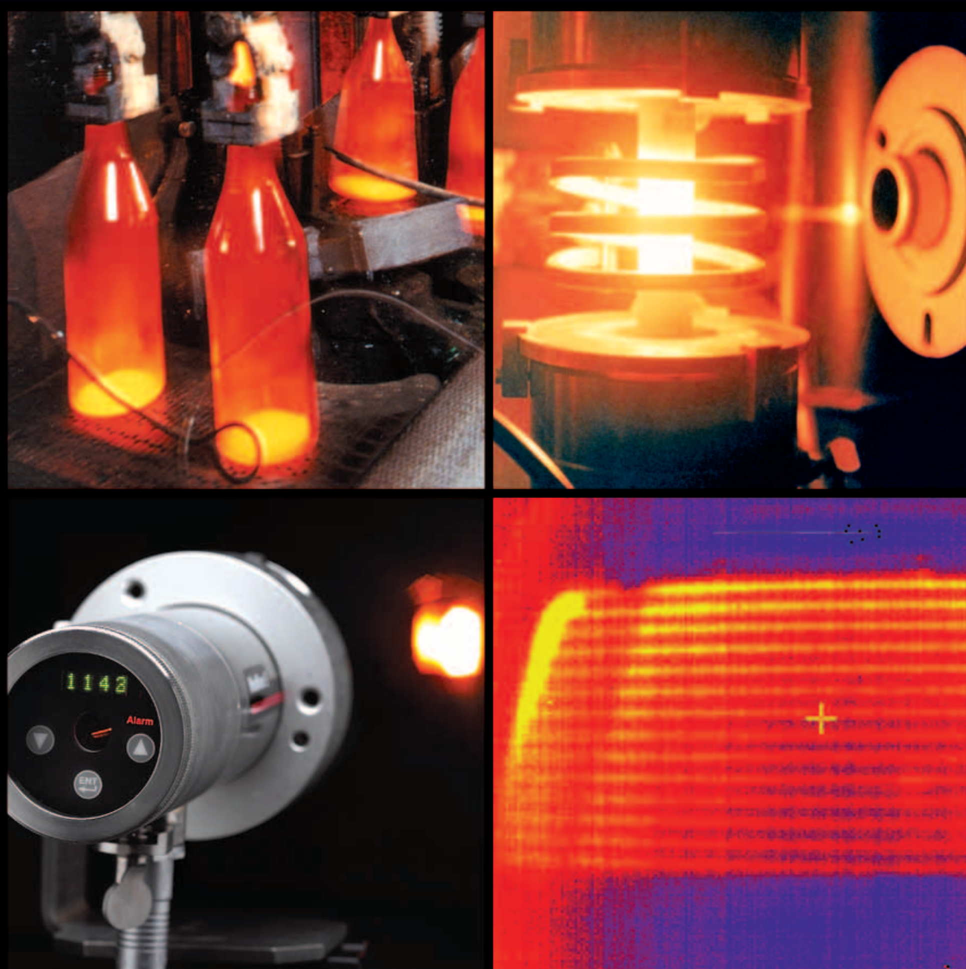
Infrared Temperature Measurement Answers and Solutions Handbook



IRCON

COMPANY HISTORY/CAPABILITIES

IRCON has been solving industry's toughest temperature measurement problems since 1962 More than 300,000 IRCON temperature measurement instruments, including a wide range of infrared thermometers, pyrometers, industrial thermal imaging systems and accessories, have been successfully installed in manufacturing facilities around the world. Designed for reliability and ruggedness, our instruments prove themselves time and time again in the most hostile environments.

To meet specific customer needs and applications, the IRCON product line offers a wide selection of on-line, non-contact infrared thermometers, including highly reliable two-color thermometers, portable thermometers, line scanners, calibration systems and accessories.

Each series of instruments offers a wide range of temperature spans and spectral regions. In addition, IRCON infrared thermometers feature through-the-lens focusable optics that allow for viewing and measuring temperatures of small targets.

IRCON provides more than a complete line of dependable equipment; it also offers total measurement solutions and a variety of support services. IRCON sales representatives and application engineers provide years of experience in solving application problems, analysis of product or material in a laboratory to assist in selecting the correct instrument, and on-site demonstrations of IRCON instruments.

In an effort to provide the best possible customer support, IRCON conducts easy-to-understand technical training seminars covering basic infrared theory in practical applications, laboratory and industrial measurement, and control problem solutions.

The IRCON Technical Services Center provides various field services, preventive maintenance contracts, calibration of instruments, and training for plant maintenance personnel.

With more than four decades of experience and a wide range of temperature measurement instruments, IRCON is constantly learning and innovating to meet the needs of customers. Smart, rugged and powerful IRCON sensing devices such as Modline 5 infrared thermometers, Maxline 2 thermal imaging systems, and ScanIR II line scanners combined with dedicated and innovative software -- IRCON is one of the leading-edge global providers of non-contact temperature measurement solutions.

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INTRODUCTION TO IR
CHAPTER 1

Infrared thermometers have the ability to measure temperature without coming into physical contact with a particular product. This ability is based on the fact that every object emits radiant energy, and the intensity of this radiation is a function of that object's temperature. The infrared thermometer simply measures the intensity of radiation, thereby measuring an object's temperature.

The following sections are designed to present the fundamentals of radiation physics upon which infrared thermometry is based. Included in the discussion will be several of the many ways of applying these fundamentals to the practical methods of temperature measurement.

RADIANT EMISSION WITH TEMPERATURE

When someone observes an object that has a sufficient amount of heat emanating from it, that object will emit light or visible radiation. This phenomenon is called incandescence. A light bulb filament, a smoldering ember and a billet of "red hot" steel are all obvious examples of this phenomenon. As the temperature of an object increases, its color and brightness will also intensify and increase. In fact, it is possible to estimate the temperature of an object in this way. Experienced workers in the steel industry, for example, visualize estimated temperatures on a regular basis.

Incandescent objects also emit a tremendous amount of "invisible" infrared radiation. For example, the radiance of a steel billet at 1,500°F is 100,000 times greater in the infrared than in the visible. This radiance is a function of the billet's temperature.

The general relationship between the radiance as a function of wavelength and temperature for a perfect emitter is shown in Figure 1. Notice that the radiance in the visible is quite low. Below 1,000°F the visible radiance is so low that we cannot see it. However, there is still copious emission of infrared radiation. Note that the radiance at every wavelength increases as temperature increases, and that the determination of the radiance at any wavelength can serve to establish the emitter's temperature.

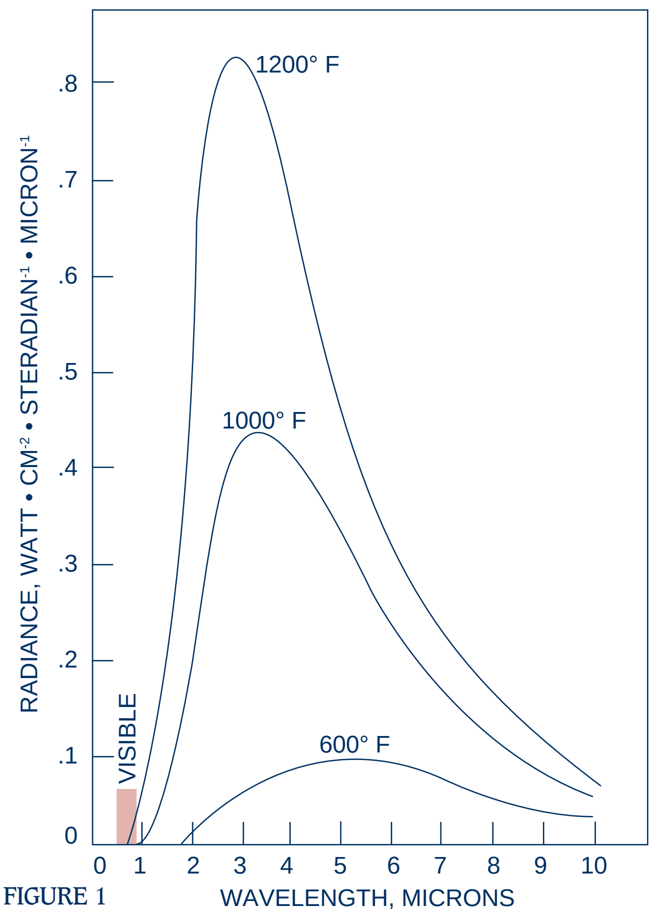


FIGURE 1
Blackbody Radiation Characteristics

NATURE OF RADIATION

The difference between infrared radiation and visible radiation is their wavelength. Red light has a longer wavelength than blue light, and infrared radiation has longer wavelengths than both of these colors. In all other aspects, these radiations behave similarly; all can be considered to be composed of elementary packets of energy called photons. Ideally, all photons travel in a straight line at the "speed of light" and can be reflected by appropriate mirrors, and their paths can be bent and focused by proper refractive elements or lenses.

All photons will dissipate their energy as heat upon being soaked up by an appropriate absorber. The only fundamental difference between a blue photon, a red photon or a two-micron infrared photon is its wavelength and the amount of energy it carries. The energy of a photon is inversely proportional to its wavelength.

ELEMENTS OF AN INFRARED THERMOMETER

A simple analysis of the eye, one form of radiation thermometer, clearly reveals the basic components used in any practical infrared thermometer. The eye contains a lens which focuses the photon flux (flow) from the emitter onto the retina or radiation detector of the human system. The retina is stimulated by the incident radiation and produces a signal that is transmitted to the brain. The brain serves as the indicator or recorder which measures the radiance of the emitter and, if properly calibrated by experience, relates this radiance to temperature.

The same basic elements make up an industrial infrared thermometer. These elements include the collecting optics, the radiation detector and some form of indicator. It is the remarkable capabilities of available detectors that result in the capabilities of present day infrared thermometers.

RADIATION DETECTORS

Radiation detectors take many forms, but all serve the same purpose of converting incident photon flux into an electrical signal (Fig. 2). The two main types are the thermal detector and the quantum detector.

A thermal detector absorbs incident flux, and the power dissipated increases the detector's temperature to change some measurable physical property (for example, its resistance). This type of detector generally has a completely black receiving surface so that it is sensitive to all wavelengths. Since the detector depends on the rising temperature within itself, it has an inherently slower response than quantum detectors.

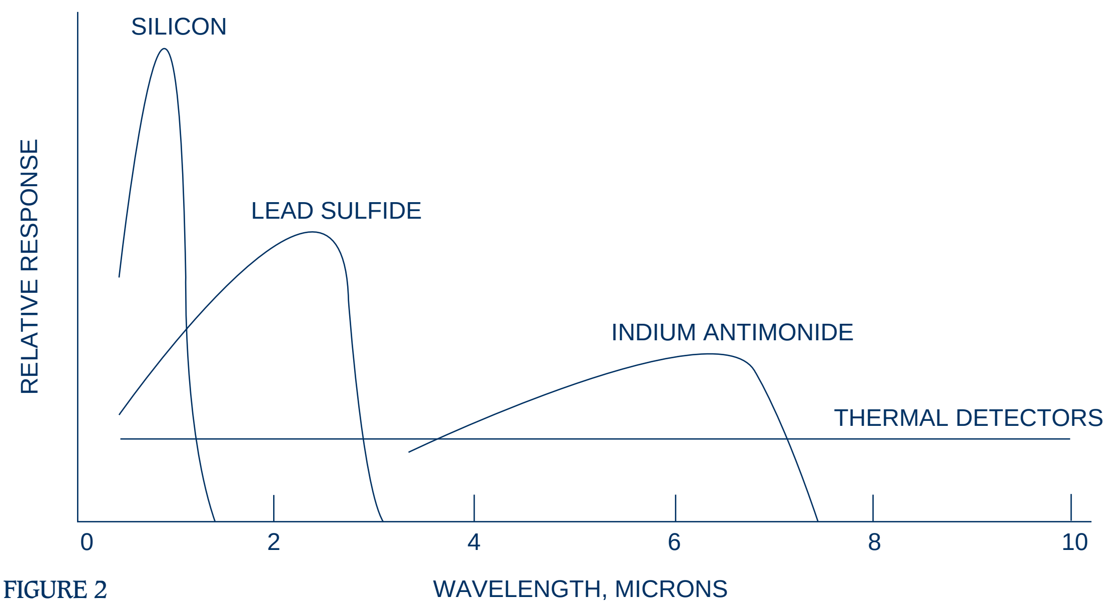


FIGURE 2
Spectral Response Characteristics of Several Infrared Detectors

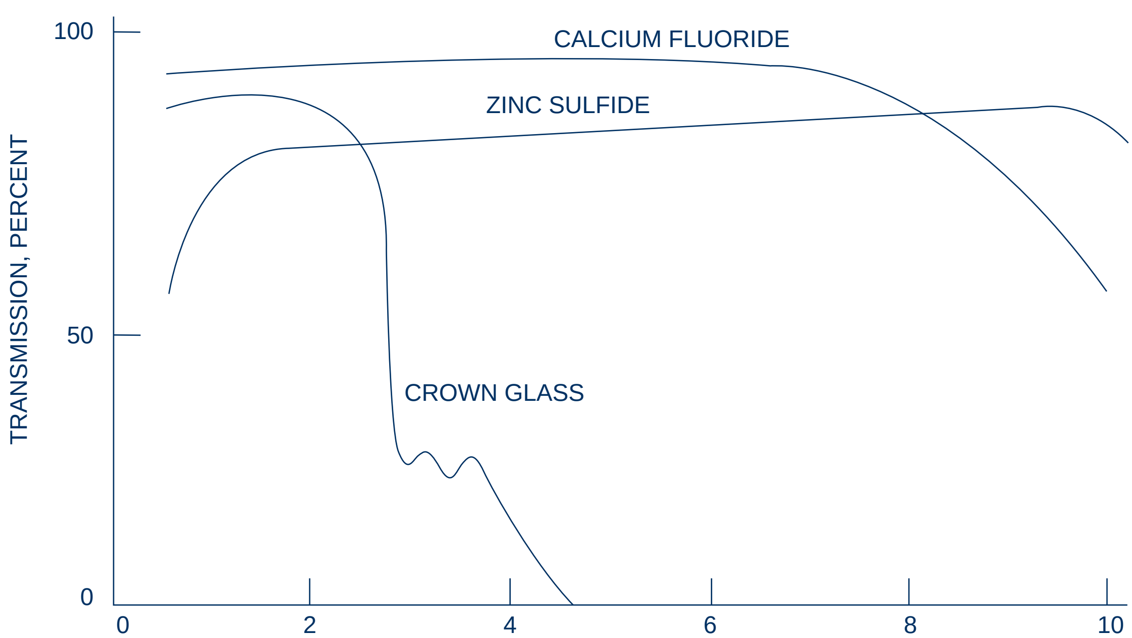


FIGURE 3
Transmission Characteristics of Several Infrared Optical Materials

A quantum detector senses radiation in a different way. One form of quantum detector, which is the type that is generally used, consists of a semiconductor crystal. The incident photon interacts with a bound electron within the crystal lattice. The photon's energy, if sufficient in size, transfers to the electron to free it from its immobile state, permitting the electron to move through the crystal. During the time the electron is free, the electron can produce a signal voltage in the detector. After a short interval, the electron will return to its bound state. This interval is generally far shorter than the thermal time constant of a thermal detector.

The quantum detector is a photon counter that is equally sensitive to all photons that have the minimum energy necessary to free a bound electron. Each detector of this type will exhibit a fairly uniform response to all photons up to a particular wavelength. Photons beyond this wavelength will not have adequate energy to free enough electrons to produce a signal.

The great practical advantage of radiation detectors is their ability to produce electrical signals that faithfully measure the incident photon flux, without requiring human attendance. This, of course, permits continuous temperature measurement and control without contact. While the eye is limited to temperature measurements above 1,000°F, present day infrared thermometers extend the measurement range down to and below -50°F.

OPTICAL ELEMENTS

The collecting optics of the infrared thermometer are selected to be compatible with the spectral response of the detector employed in a particular thermometer. Mirrors are suitable for use over wide spectral regions. Lenses, on the other hand, are restricted to those regions where the materials employed maintain good transmission properties. Certain design characteristics strongly favor the use of lenses for most practical systems. Figure 3 shows the spectral transmission properties of several infrared lens materials. These same materials are also employed as windows in those applications where the target is situated in a sealed chamber.

OUTPUT

The infrared thermometer provides an electrical voltage output which can be used for simple temperature indication or any of the many forms of closed-loop temperature control. The detector in some infrared thermometers can provide voltages high enough to drive meters and recorders directly. Other infrared thermometers, particularly those covering the lower temperature ranges, require built-in amplifiers to provide proper output levels.

CHOICE OF SPECTRAL REGION

At first glance, it would appear that an infrared thermometer should utilize the entire spectrum, or at least a broad enough portion of the spectrum to capture most of the radiant emission of the target in its particular temperature range. There are several reasons why this is not always advantageous.

RADIANCE VS WAVELENGTH

One reason for using a limited spectral region relates to the rate at which the radiance increases with temperature. An analysis of Figure 1 indicates that the radiance at two microns increases far more rapidly with temperature than it does at, say, six microns. The rate of radiance change in temperature is always greater at shorter wavelengths. The greater this rate of change, the more precise the tem-

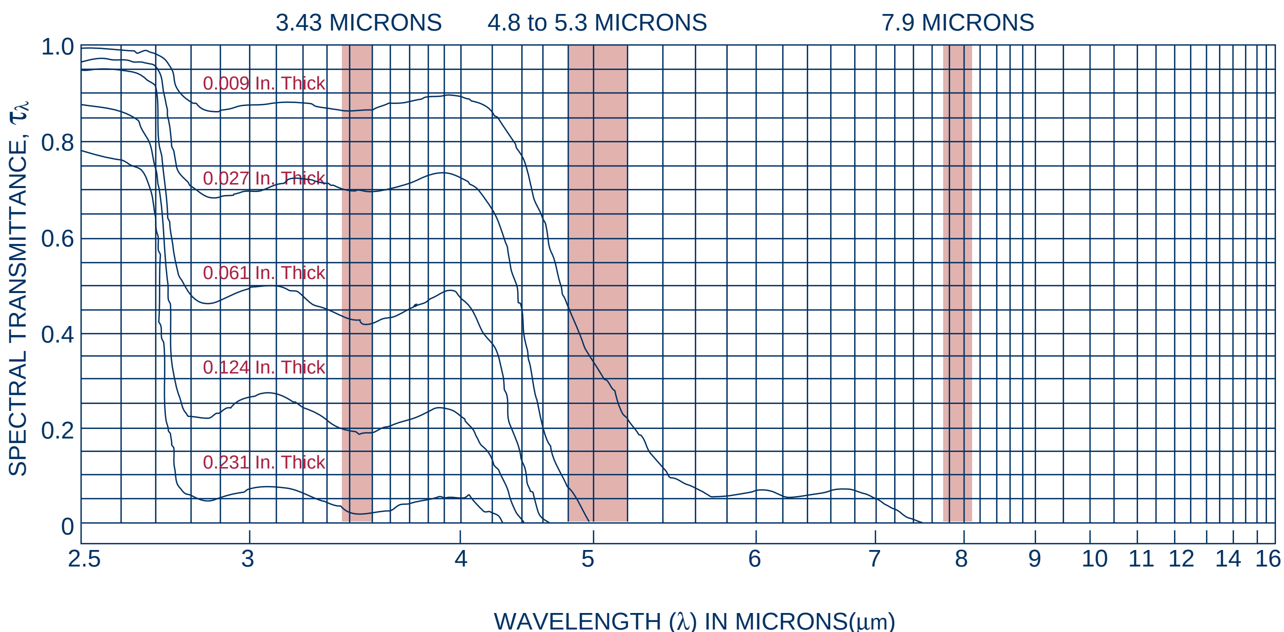


FIGURE 4

Effect of Thickness on Spectral Transmittance Curves for Soda-Lime Glass perature measurement and the tighter the temperature control. However, at a given short wavelength there is a lower limit to the temperature that can be measured. For example, the eye becomes useless for measuring temperatures below approximately 1,000°F. Similarly, the spectral range of an appropriate infrared thermometer shifts to longer wavelengths and becomes less accurate as the process temperature decreases.

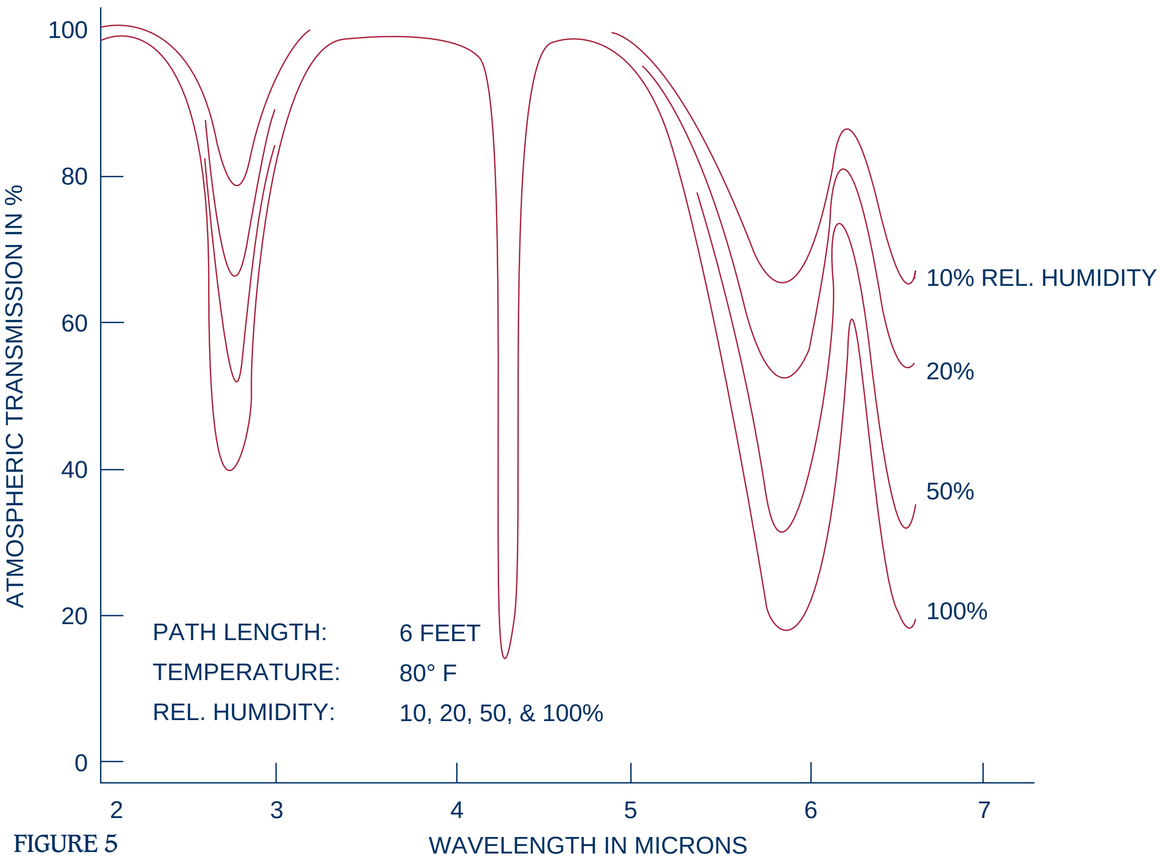


FIGURE 5

Transmission for Atmosphere at 80°F, and Several Relative Humidities

EMISSIVITY, REFLECTANCE AND TRANSMITTANCE

Another important reason for the use of different spectral regions relates to the emission characteristics of particular target materials. The curves in Figure 1 show the emission characteristics of the ideal emitter, or "blackbody." No material can emit more strongly than a blackbody at a given temperature. Many materials, however, can and do emit less than a blackbody at the same temperature in various portions of the spectrum. The ratio of the radiance at wavelength (λ) of a material to that of a blackbody at the same temperature is called the spectral emissivity (ε_λ). The value of ε_λ for the substance can range between zero and one, and this value may vary with wavelength.

The emissivity of a substance depends on its detailed interaction with radiation. A stream of radiation incident on the surface of a substance can suffer one of three fates. A portion may be reflected while another portion may be transmitted through the substance. The remainder will be absorbed and degraded to heat. The sum of the fraction reflected (r), the fraction transmitted (t) and the fraction absorbed (a) will be equal to the total amount of radiation incident on the substance. Furthermore, the emissivity (ε) of a substance is identical to the fraction absorbed (a) and can be written as:

$$\varepsilon \equiv a = 1 - t - r$$

For the blackbody, the transmitted and reflected fractions are zero and the emissivity is unity. For any opaque substance the fraction transmitted is zero and:

$$\varepsilon = 1 - r$$

An example of this case is oxidized steel in the visible and near infrared where the fraction transmitted is zero, the fraction reflected is 0.20, and the emissivity is 0.80.

A good example of a material whose emissivity characteristics change radically with wavelength is glass. Figure 4 shows the overall transmission of several specimens of soda-lime glass. The fraction reflected at the glass surface is about 0.03 or less through most of the spectral region shown. At wavelengths below about 2.6 microns, the glass is highly transparent and the emissivity is essentially zero. Beyond 2.6 microns, the glass becomes increasingly more opaque. Therefore, it is determined that beyond 4 microns, glass is completely opaque and it's emissivity is above 0.97.

This example of glass clearly illustrates how the detailed characteristics of the material can dictate the choice of the spectral region of measurement. For example, consider the problem of measuring and controlling the temperature of a glass sheet during manufacture at a point where its temperature is 1,600°F. The rule that suggests a short wavelength infrared thermometer, because of the product's high temperature, would obviously fail.

To use the region around one micron would be useless because the emissivity is close to zero. Furthermore, since the glass is highly transparent, the infrared thermometer will "see through" the glass and can give false indications because of the hot wall behind the glass. For this reason, glass can be used as an effective "window" for a short wavelength infrared thermometer.

By employing the spectral region between three and four microns, the internal temperature of the glass can be effectively measured and controlled. By operating at five or more microns, the surface temperature of the glass is measured.

ATMOSPHERIC TRANSMISSION

The third key consideration affecting the choice of spectral region is transmission through the atmosphere between target substance and infrared thermometer. The normal atmosphere always contains a small but definite amount of carbon dioxide and a variable amount of water vapor. Carbon dioxide strongly absorbs radiation between 4.2 and 4.4 microns and the water vapor absorbs strongly between 5.6 and 7.0 microns and somewhat between 2.6 and 2.9 microns (Fig. 5). Analyzing this information indicates that these spectral regions should be avoided, particularly in the region of the water bands. If not avoided, the temperature calibration will vary with path length and humidity. If the air temperature is comparable to, or higher than, the target temperature, an improperly designed infrared thermometer could provide temperature measurements that are strongly influenced by air temperature.

PRACTICAL APPLICATIONS

Infrared thermometers are currently used in a wide range of laboratory and industrial temperature control applications. A few low temperature examples include extrusion, lamination and drying of plastics, paper and rubber in the curing process of resins, adhesives and paints. Another low temperature example of an infrared thermometer can be found in the steel industry where these instruments are used in the cold rolling and forming of metals.

Some high temperature examples include forming, tempering and annealing of glass; smelting, casting, rolling, forging and heat treating of metals; and calcining and firing of ceramics and cement. Other types of applications can be found on page 24.

In short, an infrared thermometer can be used in almost any application in the range from -50 to 6,500°F where the instruments' unique capabilities can turn a seemingly impossible measurement and control problem into a practical working process. Many processes now controlled manually can be converted into continuous, automated systems.

The intent of the following chapters is to clarify some of the misconceptions about using infrared thermometers and to show what some of the possible effects are that could contribute to an erroneous temperature indication. IRCON'S philosophy is that if you understand the major contributors to misapplication of infrared thermometers, you will be better prepared to understand your temperature measurement results, and prepared to choose the correct instrument for your application.

TEMPERATURE EFFECTS CAUSED BY PRODUCT EMISSIVITY
CHAPTER 2

The focus of the following four chapters will be the examination of areas that affect the decision-making process in determining how and when to use brightness infrared thermometry. Chapter 2 will examine emissivity as the cause of temperature error when using an infrared brightness thermometer. Subsequent parts of this chapter will examine optical path, transmission, hot backgrounds and the infrared thermometer itself as additional sources of temperature error in determining how and when to use an infrared thermometer.

COMPONENTS OF TEMPERATURE ERROR

Learning that the indicated target temperature may not be a true target measurement is only part of the problem in determining emissivity . The following formula represents the total temperature error of a system (ΔT_{SYSTEM}) and the components that contribute to this error.

$$\Delta T_{SYSTEM} = \Delta T_{EMISSIVITY} + \Delta T_{TRANSMISSION} + \Delta T_{BACKGROUND} + \Delta T_{INSTRUMENT}$$

This formula indicates that total temperature error is caused by a combination of the following components: an emissivity error, a transmission error, a background error and an error in the instrument itself. Each component error may be positive, negative or zero.

The red areas of this formula represent what are referred to as application errors. These are errors that may be controlled by the instrument user. Improper applications are the primary contributors to the total error. The instrument error is often the smallest part of the total error. To understand temperature errors more completely, each variable component of the formula will be analyzed individually. With care, all of these errors can be reduced to acceptable levels.

EMISSIVITY AND TEMPERATURE MEASUREMENT

Infrared radiation thermometer users have wrestled with emissivity since temperature measurement technology was first applied to leading industrial processes. Users of infrared brightness thermometers have learned that a true target temperature measurement can be achieved only when the correct target emissivity is set on the instrument dial. When the instrument emissivity dial is set incorrectly, a temperature error results.

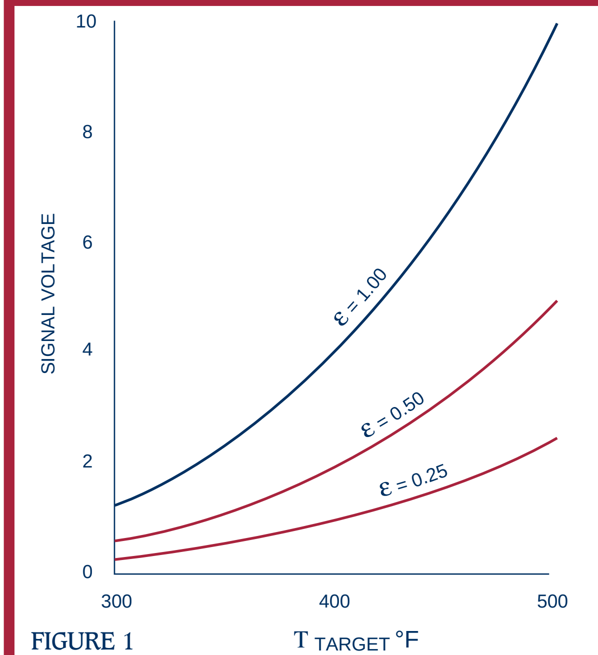


FIGURE 1

Signal Voltage/Temperature Curves

How does target emissivity influence the temperature measurement of an infrared thermometer? An instrument is designed to collect the radiation emanating from a target and measure that radiance quantitatively. The circuitry of the instrument produces a signal voltage from which a temperature is then indicated. This indicated temperature is proportional to the target radiance. Figure 1 illustrates signal voltage versus target temperature curves for three targets with different emissivities.

The curve labeled ε = 1.00 represents the signal voltage output when an instrument views a blackbody. The curves labeled ε = 0.50 and ε = 0.25 represent the signal voltage output when the same instrument views targets with lower emissivities. While the shape of the latter curves are the same, the signal magnitudes are reduced by the emissivities 0.50 and 0.25.

In order for an instrument to indicate true temperature, the emissivity dial setting must correspond to the target emissivity. This dial is a calibrated gain adjustment which allows the user to trim the instrument to the emissivity of a target. When it is set correctly, the instrument indicates the target temperature without error. Figure 2 illustrates the position of the emissivity gain adjustment between the sensing head and the linearizer.

COMPUTE THE TEMPERATURE ERROR

The magnitude of temperature error created by uncertainty in a given emissivity depends on the spectral range of the infrared thermometer and the target temperature. The Error Tables (1F and 1C) represent indicated temperature errors caused by one-percent emissivity errors. These tables may also be used to compute temperature errors caused by emissivity errors greater than one percent.

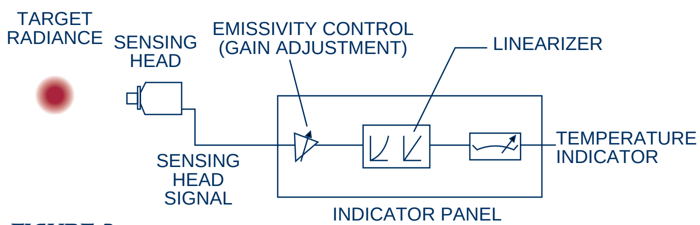


FIGURE 2

Infrared Temperature Measuring System Illustrating Emissivity Control

Reasonable accuracy can be expected with emissivity errors up to 40 percent. To compute a temperature error caused by an incorrect emissivity setting, simply use the following formula:

$$\Delta T = -100 \times \left[\frac{\varepsilon_{DIAL} - \varepsilon_{TRUE}}{\varepsilon_{TRUE}}\right] \times \Delta T_{TABLE}$$

EXAMPLE I

Emissivity Dial is Set Incorrectly:

Calculate the temperature error caused by an emissivity error in measuring steel on the hot strip mill using the IRCON® Series operating at 0.9 µm. The true temperature is 1,800°F and the ε_{TRUE} is 0.82. An operator mistakenly sets the ε_{DIAL} to 0.70. It will be necessary to refer to table 1F for this temperature error.

$$\Delta T = -100 \times \left[\frac{\varepsilon_{DIAL} - \varepsilon_{TRUE}}{\varepsilon_{TRUE}}\right] \times \Delta T_{TABLE}$$

$$= -100 \times \left[\frac{0.70 - 0.82}{0.82}\right] \times 1.8°F$$

$$\Delta T = +26°F$$

For this example, the temperature error is 26°F.

EXAMPLE II

Variations in Emissivity During a Process Run:

The various paints used on a coil coating line exhibit varying emissivities to the series operating at 3.4 µm. The values range from 0.91 for the vinyls to 0.95 for the polyesters.

The operator sets ε_{DIAL} to 0.93: the geometric mean for all paint types. All paints are heated to 400°F. Use the same formula to determine ±2°F temperature error for this production run.

See box on page 8 for summary of symbols.

TABLE 1F – BRIGHTNESS THERMOMETER TEMPERATURE EFFECTS CAUSED BY A ONE PERCENT SHIFT IN EMISSIVITY (In Degrees Fahrenheit)

EFFECTIVE WAVELENGTH	0.65µm	0.9µm	1.6µm	2.3µm	3.4µm	3.9µm	5.0µm	8.0µm	10.6µm
TARGET TEMPERATURE (°F)									
0	0.05	0.07	0.13	0.18	0.27	0.31	0.41	0.64	0.86
200	.10	.14	.27	.38	.57	.64	.85	1.3	1.7
400	.18	.25	.46	.66	.97	1.1	1.4	2.2	2.8
600	.28	.38	.70	1.0	1.5	1.7	2.2	3.3	4.1
800	.40	.55	1.0	1.4	2.1	2.3	3.1	4.5	5.6
1000	.53	.73	1.3	1.9	2.8	3.1	4.1	5.8	7.1
1200	.69	.95	1.7	2.5	3.6	4.0	5.2	7.2	8.7
1400	.87	1.2	2.2	3.1	4.5	5.0	6.4	8.8	10
1600	1.1	1.5	2.7	3.8	5.5	6.1	7.6	10	12
1800	1.3	1.8	3.2	4.5	6.5	7.2	9.0	12	14
2000	1.5	2.1	3.8	5.4	7.6	8.4	10	14	16
2200	1.8	2.5	4.5	6.2	8.8	9.7	12	15	17
2400	2.1	2.8	5.2	7.2	10	11	13	17	19
2600	2.4	3.3	5.9	8.2	11	12	15	19	21
2800	2.7	3.7	6.7	9.2	13	14	17	21	23
3000	3.0	4.2	7.5	10	14	15	18	22	25
3500	4.0	5.4	9.8	12	18	19	22	27	30
4000	5.1	6.9	12	16	21	23	27	32	34
4500	6.3	8.5	15	20	25	27	31	36	39
5000	7.6	10	18	23	30	31	36	41	44

For temperature errors caused by shifts in Emissivity greater than 1%, use the formula illustrated in the example below.

Example:

INSTRUMENT	SERIES(1.6µm)
T_{IND}	1000°F
ε_{DIAL}	0.70
ε_{TRUE}	0.82

$$\Delta T = -100 \times \left[\frac{\varepsilon_{DIAL} - \varepsilon_{TRUE}}{\varepsilon_{TRUE}}\right] \times \Delta T_{TABLE}$$

$$= -100 \times \left[\frac{0.70 - 0.82}{0.82}\right] \times 1.3°F$$

$$\Delta T = +19°F$$

To determine T_{TRUE} for this example, use the following formula:

$$T_{TRUE} = T_{IND} - \Delta T$$

$$= 1000°F - 19°F$$

$$T_{TRUE} = 981°F$$

TABLE 1C – BRIGHTNESS THERMOMETER TEMPERATURE EFFECTS CAUSED BY A ONE PERCENT SHIFT IN EMISSIVITY (In Degrees Celsius)

EFFECTIVE WAVELENGTH	0.65μm	0.9μm	1.6μm	2.3μm	3.4μm	3.9μm	5.0μm	8.0μm	10.6μm
TARGET TEMPERATURE (°C)									
0	0.03	0.04	0.08	0.12	0.17	0.20	0.26	0.41	0.54
100	.06	.08	.15	.22	.33	.37	.49	.76	1.0
200	.10	.14	.25	.36	.53	.60	.79	1.2	1.6
300	.15	.20	.37	.53	.78	.87	1.2	1.7	2.2
400	.20	.28	.51	.73	1.1	1.2	1.6	2.3	2.9
500	.27	.37	.68	.96	1.4	1.6	2.1	3.0	3.6
600	.35	.47	.87	1.2	1.8	2.0	2.6	3.7	4.4
700	.43	.59	1.1	1.5	2.2	2.5	3.2	4.4	5.2
800	.52	.72	1.3	1.8	2.7	3.0	3.8	5.2	6.1
900	.63	.86	1.6	2.2	3.2	3.5	4.4	6.0	7.0
1000	.74	1.0	1.8	2.6	3.7	4.1	5.1	6.8	7.8
1100	.86	1.2	2.2	3.0	4.3	4.7	5.8	7.6	8.7
1200	.99	1.4	2.5	3.4	4.9	5.4	6.6	8.5	9.6
1300	1.1	1.6	2.8	3.9	5.5	6.0	7.3	9.3	11
1400	1.3	1.8	3.2	4.4	6.1	6.7	8.1	10	11
1500	1.4	2.0	3.6	4.9	6.8	7.4	8.9	11	12
1600	1.6	2.2	4.0	5.5	7.5	8.1	9.6	12	13
1800	2.0	2.7	4.8	6.5	8.9	9.6	11	14	15
2000	2.4	3.2	5.8	7.7	10	11	13	16	17
2200	2.8	3.8	6.8	9.0	12	13	15	18	19
2400	3.3	4.5	7.8	10	13	14	16	19	21
2600	3.8	5.1	9.0	12	15	16	18	21	23
2800	4.3	5.9	10	13	17	18	20	23	25
3000	4.9	6.6	11	15	18	20	22	25	27

For temperature errors caused by shifts in Emissivity greater than 1%, use the formula illustrated in the example below.

Example: INSTRUMENT SERIES (1.6μm)

T_{IND}	500°C
ε_{DIAL}	0.70
ε_{TRUE}	0.82

$$\Delta T = -100 \times \left[\frac{\varepsilon_{DIAL} - \varepsilon_{TRUE}}{\varepsilon_{TRUE}}\right] \times \Delta T_{TABLE}$$

$$= -100 \times \left[\frac{0.70 - 0.82}{0.82}\right] \times 0.68°C$$

$\Delta T = +9.95°C$

To determine T_{TRUE} for this example, use the following formula:

$$T_{TRUE} = T_{IND} - \Delta T$$
$$= 500°C - 10°C$$
$$T_{TRUE} = 490°C$$

SYMBOL	DEFINITION
T_{IND}	Target Temperature Indicated by Instrument
T_{TRUE}	True Target Temperature
ΔT	Indicated Temperature Error: $T_{IND} - T_{TRUE}$
ΔT_{TABLE}	Error Value in from Tables 1F and 1C
ε_{DIAL}	Actual Emissivity Setting on Instrument Dial
ε_{TRUE}	True Target Emissivity

TEMPERATURE EFFECTS DUE TO TRANSMISSION LOSSES
CHAPTER 3

IMPORTANCE OF THE TRANSMISSION PATH

An infrared brightness thermometer determines an object's temperature by quantitatively measuring its radiance. In order to measure radiance, the instrument must have a constant and predictable view of its target. Under ideal conditions, ensuring this perspective can be accomplished by simply filling the field of view with the target; the amount of radiant energy received at the detector is determined by the target's temperature. In reality, however, some radiation is lost in the "transmission path" between the emitting surface and the detector. If this loss is significant, the brightness thermometer detects less radiation than it should and indicates a temperature that is too low.

Transmission losses are caused by objects, particles and even gas molecules which lie within the optical transmission path, as illustrated in Fig. 1. The intervening materials absorb, reflect or "scatter" some of the emitted radiation before it reaches the detector within the sensing head. The transmission losses increase with longer path lengths, yet the instrument cannot be placed too close to a hot target. Close proximity to a hot target can result in overheating and permanent damage. It is possible, however, to minimize some transmission loss problems. For instance, instruments can be designed to avoid particular wavelength bands that are absorbed in the transmission path. Water vapor and CO_2, which are the primary atmospheric absorbers in the near infrared, have little effect on IRCON infrared brightness thermometers.

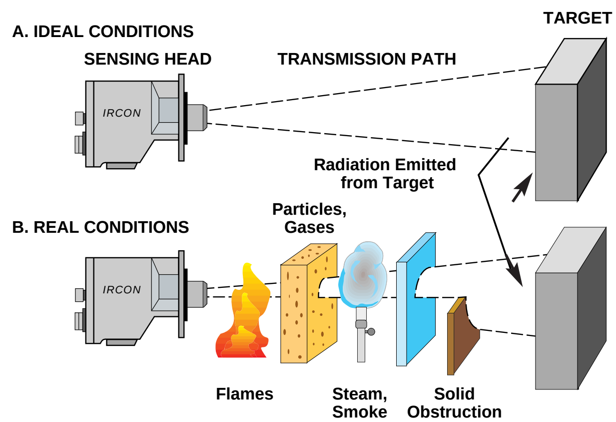


FIGURE 1

Materials in Transmission Path Reduce Radiation Entering Sensing Head

AVOIDING TRANSMISSION ERRORS

Serious and unnecessary transmission losses can often be prevented with proper care, installation and use of a brightness thermometer. The lens within the instrument and any windows must be kept clean of dirt, oil and other evaporated buildup. The unit must also be focused so that its transmission path is clear of all solid, opaque objects. It is equally important that any windows or sight holes are made large enough that no part of the "cone of vision" is cut off.

Procedures for cleaning optical components and for sighting instruments are included in the operations manuals and can be supplemented by consulting the IRCON Technical Service Department. In some applications, transmission problems can be avoided simply. For example, transmission loss resulting from smoke can be eliminated if the angle of view is moved from the top of the product where smoke is rising, to the bottom of the product where a clear field of view can be established.

COMPENSATING FOR LOSS

In cases where transmission losses are known, it is possible to compensate for them. Just as an emissivity (ε) value of 1.0 represents a perfect radiator, a transmission (τ) value of 1.0 represents a completely transparent material or path. When some radiation is lost, the transmission has a lower (fractional) value. When the radiation is completely blocked off, of course, the transmission is zero.

True temperature readings are possible only if the signal voltages are at the calibrated levels obtained when viewing an ideal (blackbody) radiator. Figure 2 shows that when both ε_{TARGET} and τ_{PATH} are less than perfect, both factors contribute to losses in the detected radiant energy. These losses may simply be looked upon as an effective emissivity value (ε_{EFF}), since the source of the loss makes no difference to the instrument. Therefore, the emissivity dial can be set to compensate for total loss.

The signal voltages produced by the detector are correctly amplified to blackbody levels when the dial is set to the value:

$$\varepsilon_{EFF} = \varepsilon_{TARGET,\ TRUE} \times \tau_{PATH,\ TRUE} \qquad (1)$$

For example, if a window is the only object in the transmission path that causes a significant loss, $\tau_{PATH} = \tau_{WINDOW}$. If $\varepsilon_{TARGET} = 0.80$ and $\tau_{WINDOW} = 0.85$, the emissivity dial should be set to 0.80 x 0.85 = 0.68.

ERROR CALCULATION

If there is an error in the transmission value used to determine the dial setting, there is also an error in the indicated temperature. NOTE: It is assumed in this section that the target's true emissivity value is always known and correctly taken into account. The magnitude of this temperature error varies with both the target's temperature and the instrument's spectral region. Tables 1 and 2 show representative temperature error values that result from a one percent transmission error. The effect of larger errors may be calculated by multiplying the percentage of transmission error* times the effect of a one percent error as follows:

$$\Delta T = 100 \times \left[\frac{\varepsilon_{EFF} - \varepsilon_{DIAL}}{\varepsilon_{EFF}}\right] \times \Delta T_{TABLE} \qquad (2)$$

Where ε_{EFF} is given by equation (1). See Figure 3 for summary of symbols. This formula may be used with reasonable accuracy for transmission errors up to 40 percent.

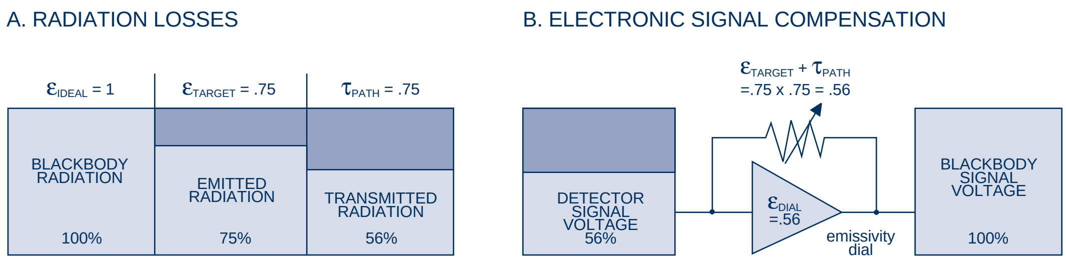


FIGURE 2

An Infrared Brightness Thermometer can Compensate for Radiation Losses (A), If the Emissivity Dial is Set to the Proper Value (B)

TRANSMISSION THROUGH WINDOWS

Whereas most transmission loss varies with changing environmental conditions, the transmission loss caused by a window remains constant (as long as it is kept clean, stationary, etc.). Therefore, windows afford the simplest example for calculating the effects of transmission errors. Errors can result from uncertainty in the transmission value or from the very common mistake of neglecting the effect of the window entirely. It is also important to realize that transmission of a window material is not the same for all wavelengths.

EXAMPLE I
CORRECTING FOR THE EFFECT OF A WINDOW:

Some silicon wafers are enclosed in the quartz bell jar of an epitaxial reactor. For successful processing, the wafers must be heated to a temperature of 1,800° F. A typical thermometer operating at 0.9µm is used to monitor the temperature of the wafers, which have an emissivity of 0.66. In order to do this, however, the instrument must view through the bell jar, which has a transmission of 0.94 at 0.9µm. How is the indicated temperature affected if the operator forgets to compensate for transmission losses and corrects for target emissivity only? The answer can be found by using equation (2), as follows:

$$\Delta T = 100 \times \left[\frac{\varepsilon_{EFF} - \varepsilon_{DIAL}}{\varepsilon_{EFF}}\right] \times \Delta T_{TABLE}$$

In this case,

$$\varepsilon_{EFF} = \varepsilon_{TARGET} \times \tau_{WINDOW} = .66 \times .94 = .62$$

$$\varepsilon_{DIAL} = \varepsilon_{TARGET} = .66$$

$$\Delta T_{TABLE} = 1.8°$$

so

$$\Delta T = 100 \times \left[\frac{.62 - .66}{.62}\right] \times 1.8° = -12°F$$

The indicated temperature is 12° F lower than the true temperature.

Notice from Tables 1 and 2 that the ΔT_{TABLE} values increase with rising temperatures. Therefore, the temperature error in the above example would be worse if the process temperature was increased.

EXAMPLE II
STEAM INTERFERENCE:

A steel strip in a rolling mill has a temperature of 1,680°F as it exits the final finishing stand. A typical thermometer operating at 0.9µm with an emissivity dial setting of 0.82, the emissivity of the steel, indicates the correct temperature when the process begins. Gradually, water from nearby cooling sprays starts to evaporate off the hot steel, generating steam. A recorder connected to the thermometer begins charting a series of jagged spikes showing temperature variations of at least 80° F as the process continues. Can the emissivity dial be set to compensate for serious steam interference? What is the temperature error?

Answer: There is, of course, no dial setting that always produces a correct temperature indication. Varying amounts of steam continually flow through the optical path causing the transmission of the path to vary unpredictably. This results in the instrument's chart recorder producing a jagged tracing. Equation (2) can be solved for τ_{PATH} to find, for instance, that the transmission was 0.67 when the indicated temperature had dropped to 80°F (assuming the true temperature stayed the same). Although the exact amount of error continually varies, the steam clearly has a significant effect on the indicated temperature.

MINIMIZING TRANSMISSION ERRORS

Transmission errors generally are minimized by using the shortest wavelength unit capable of measuring the specified temperature range. Tables 1 and 2 show that the ΔT_{TABLE} error values become larger for longer wavelength units. Therefore, transmission losses comparable to those in the above example

The percentage of transmission error is the same as the percentage of dial setting error when the target's true emissivity value is known.

would result in even more severe temperature errors if a longer wavelength unit were used.

There are several accessories for IRCON brightness thermometers which may be used to further minimize transmission problems. Interferences like steam and smoke are carried on turbulent air currents which occasionally allow a clear glimpse of the target. A "peak picking" option allows a unit to latch onto the highest "clear" reading, greatly improving the accuracy of the indicated temperature. The "sight tube" option is useful for shielding the optical path from transmission interferences. Finally, the "air purge" option helps to prevent particles from settling on an instrument's lens.

TABLE 1 – BRIGHTNESS THERMOMETER TEMPERATURE ERRORS CAUSED BY ONE PERCENT TRANSMISSION ERRORS (In Degrees Fahrenheit)

EFFECTIVE WAVELENGTH	0.65µm	0.9µm	1.6µm	2.3µm	3.4µm	3.9µm	5.0µm	8.0µm	10.6µm
TARGET TEMPERATURE (°F)									
0	0.05	0.07	0.13	0.18	0.27	0.31	0.41	0.64	0.86
200	.10	.14	.27	.38	.57	.64	.85	1.3	1.7
400	.18	.25	.46	.66	.97	1.1	1.4	2.2	2.8
600	.28	.38	.70	1.0	1.5	1.7	2.2	3.3	4.1
800	.40	.55	1.0	1.4	2.1	2.3	3.1	4.5	5.6
1000	.53	.73	1.3	1.9	2.8	3.1	4.1	5.8	7.1
1200	.69	.95	1.7	2.5	3.6	4.0	5.2	7.2	8.7
1400	.87	1.2	2.2	3.1	4.5	5.0	6.4	8.8	10
1600	1.1	1.5	2.7	3.8	5.5	6.1	7.6	10	12
1800	1.3	1.8	3.2	4.5	6.5	7.2	9.0	12	14
2000	1.5	2.1	3.8	5.4	7.6	8.4	10	14	16
2200	1.8	2.5	4.5	6.2	8.8	9.7	12	15	17
2400	2.1	2.8	5.2	7.2	10	11	13	17	19
2600	2.4	3.3	5.9	8.2	11	12	15	19	21
2800	2.7	3.7	6.7	9.2	13	14	17	21	23
3000	3.0	4.2	7.5	10	14	15	18	22	25
3500	4.0	5.4	9.8	13	18	19	22	27	30
4000	5.1	6.9	12	16	21	23	27	32	34
4500	6.3	8.5	15	20	25	27	31	36	39
5000	7.6	10	18	23	30	31	36	41	44

SYMBOL	DEFINITION
T_{IND}	Target Temperature Indicated by Instrument
T_{TRUE}	True Target Temperature
ΔT	Indicated Temperature Error: $T_{IND} - T_{TRUE}$
ΔT_{TABLE}	Error Value in from Tables 1F and 1C
ε_{DIAL}	Actual Emissivity Setting on Instrument Dial
ε_{EFF}	Emissivity Setting Required for $T_{IND} = T_{TRUE}$
$\varepsilon_{TARGET, TRUE}$	True Target Emissivity
$\tau_{PATH, TRUE}$	True Path Transmission

FIGURE 3

TABLE 2 – BRIGHTNESS THERMOMETER TEMPERATURE ERRORS
CAUSED BY ONE PERCENT TRANSMISSION ERRORS (In Degrees Celsius)

EFFECTIVE WAVELENGTH	0.65µm	0.9µm	1.6µm	2.3µm	3.4µm	3.9µm	5.0µm	8.0µm	10.6µm
TARGET TEMPERATURE (°C)									
0	0.03	0.04	0.08	0.12	0.17	0.20	0.26	0.41	0.54
100	.06	.08	.15	.22	.33	.37	.49	.76	1.0
200	.10	.14	.25	.36	.53	.60	.79	1.2	1.6
300	.15	.20	.37	.53	.78	.87	1.2	1.7	2.2
400	.20	.28	.51	.73	1.1	1.2	1.6	2.3	2.9
500	.27	.37	.68	.96	1.4	1.6	2.1	3.0	3.6
600	.35	.47	.87	1.2	1.8	2.0	2.6	3.7	4.4
700	.43	.59	1.1	1.5	2.2	2.5	3.2	4.4	5.2
800	.52	.72	1.3	1.8	2.7	3.0	3.8	5.2	6.1
900	.63	.86	1.6	2.2	3.2	3.5	4.4	6.0	7.0
1000	.74	1.0	1.8	2.6	3.7	4.1	5.1	6.8	7.8
1100	.86	1.2	2.2	3.0	4.3	4.7	5.8	7.6	8.7
1200	.99	1.4	2.5	3.4	4.9	5.4	6.6	8.5	9.6
1300	1.1	1.6	2.8	3.9	5.5	6.0	7.3	9.3	11
1400	1.3	1.8	3.2	4.4	6.1	6.7	8.1	10	11
1500	1.4	2.0	3.6	4.9	6.8	7.4	8.9	11	12
1600	1.6	2.2	4.0	5.5	7.5	8.1	9.6	12	13
1800	2.0	2.7	4.8	6.5	8.9	9.6	11	14	15
2000	2.4	3.2	5.8	7.7	10	11	13	16	17
2200	2.8	3.8	6.8	9.0	12	13	15	18	19
2400	3.3	4.5	7.8	10	13	14	16	19	21
2600	3.8	5.1	9.0	12	15	16	18	21	23
2800	4.3	5.9	10	13	17	18	20	23	25
3000	4.9	6.6	11	15	18	20	22	25	27

TEMPERATURE EFFECTS DUE TO BACKGROUND RADIATION CHAPTER 4

PROBLEM OF BACKGROUND SOURCES

The basic relationship used in infrared thermometry is that the intensity, or brightness, of infrared radiation emitted by an object increases predictably with its temperature.

Unfortunately, an infrared brightness thermometer cannot distinguish between the radiation which a target emits and the radiation originating from other sources.

If the detected radiation includes radiation from the target and an additional component originating from background sources, the indicated temperature is higher than the target's true temperature.

All spatial area is filled with radiation emitted by the physical matter in the environment. Any radiation emitted by sources other than the selected target object is referred to as "background radiation."

This radiation can encompass wavelengths throughout the electromagnetic spectrum, including visible and infrared. The intensities at the infrared wavelengths (as with all the other wavelengths) are determined by the temperatures and emissivities of the objects in the surroundings, as well as by the presence of absorbing materials in the transmission paths.

Background radiation does not present a problem to temperature measurement unless it has a significant intensity. The intensity is significant when the brightness of the background sources at the detected wavelength is comparable to, or greater than, that of the target. At that point, the extra radiation contributed by the background may make enough of a difference to increase the indicated temperature.

Analogously, it is easy to see that a flashlight beam adds significantly to the light from a match, but makes no real difference when it is added to the beam from a searchlight. The brightness of the flashlight is not significant if the target source is much brighter.

Since the human eye cannot see infrared radiation, it is impossible to know if background radiation is significant enough to produce an effect. We can estimate the significance of the background's radiance, relative to the target's, simply by comparing the approximate temperatures of the target and background sources.

Although many other factors affect how much background radiation is actually detected, this basic relationship still provides a good way to identify potential background interferences.

For example, when a target is heated well above room temperature, the radiation emitted by room temperature objects is negligible in comparison to the detected radiation from the target. If the room is lit with tungsten filament bulbs, however, the radiation produced by the high-temperature filaments could add significantly to the detected target radiation.

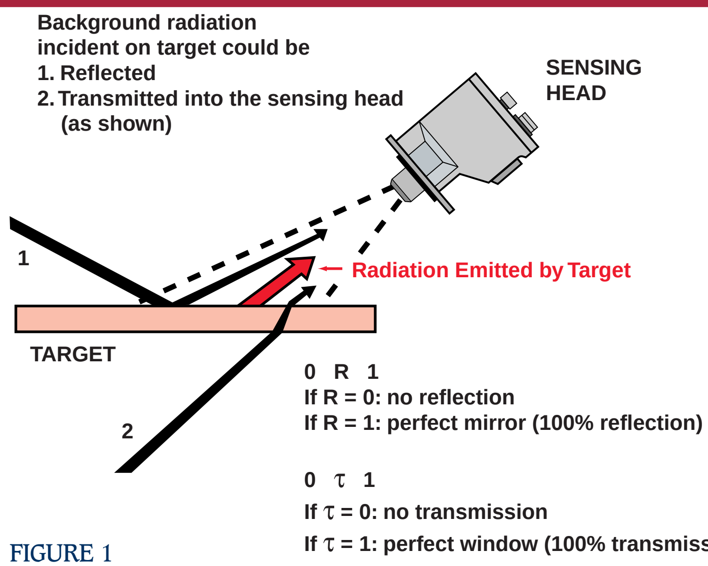


FIGURE 1

Background Radiation Can Contribute to Detected Radiation if τ_{TARGET} or R_{TARGET} is Greater than zero (The target absorbs the portion of incident background radiation which is neither reflected nor transmitted).

Similarly, intense plant lighting or inspection lighting can cause problems. Other hot surfaces and hot objects near the target are also important sources of background interference.

DETECTION OF BACKGROUND RADIATION

Under what circumstances does the detected radiation include an added component from background sources? An obvious case is when the target does not completely fill the instrument's field of view. Then the unit also "sees" beyond the target into the background.

A correctly operated brightness thermometer, however, is aimed so that the target completely fills its field of view. Under these conditions, no background radiation can be detected unless the target has transmissive or reflective properties.

Therefore, background radiation can be a problem only if the target acts something like a mirror, a window, or both, in the detected infrared spectral region. Note that an object which is reflective or transparent to visible radiation is not necessarily reflective or transparent to infrared radiation, and vice versa.

The target's reflectivity (R) and transmittance (τ) factors at the detected wavelength affect the size of the contribution made by background radiation to the detected energy. As shown in Figure 1, these factors can take on values from zero to one, representing the fraction of incident background radiation that is reflected or transmitted.

Thus, even when there is a relatively large amount of background radiation, there still may be very little error in temperature measurement. The target may reflect or transmit only a small fraction of the background radiation to the infrared thermometer.

The target's emissivity value is the indicator of how susceptible it is to background interferences. This is because an object's emissivity (ε) is related to its transmissive (τ) and reflective (R) properties by the formula:

$$\varepsilon = 1 - R - \tau \quad (1)$$

For instance, a "blackbody" is a perfect radiator and has an emissivity of one. When the emissivity value equals one, both the reflectivity and transmittance must be zero.

Because such a target does not reflect or transmit any radiation, the measurements do not contain errors due to background radiation. This is true no matter how much background radiation there is.

However, nearly all real targets have emissivity values which are less than one. Because of this, the detected radiant energy usually has at least some contribution (due to reflection and/or transmission) from the background.

It is clearly beneficial to detect radiation in a spectral region where the target has a high emissivity. This is one of the reasons that IRCON products offer such a wide range of instruments with different spectral responses.

Generally instruments are selected so that the target has no transmission and as little reflection as possible in the detected spectral region. This makes the problem of avoiding significant background radiation a little easier.

To summarize the preceding discussion, the lower the target emissivity, the greater the fraction of radiation the target reflects and/or transmits from the background. However, if there is not much radiation in the background to begin with, the extra contribution to the detected energy is very small.

If there is a significant amount of background radiation, there may be enough energy detected to cause an erroneously high temperature indication.

FIGURE 2(A)

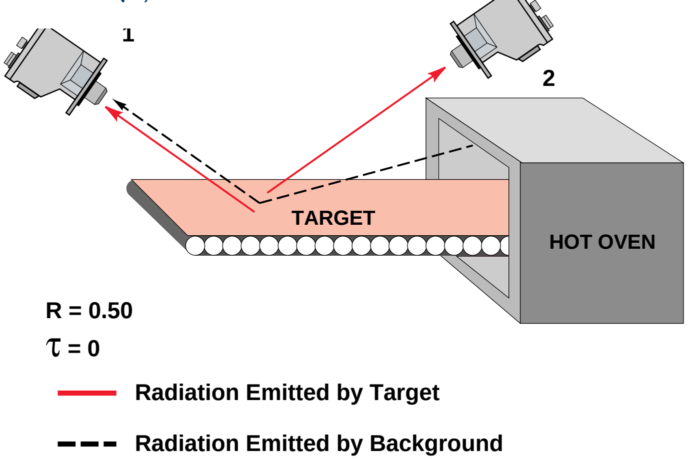
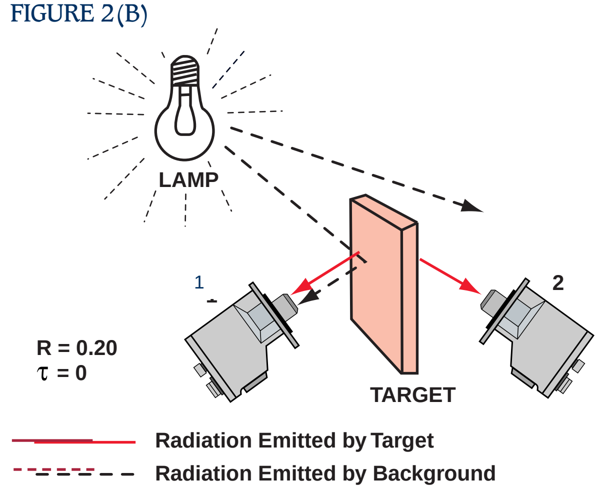


FIGURE 2(B)



Proper Positioning of the Sensing Head can Avoid Significant Background Errors. (A) Unit 2 Avoids First-Order Reflections; Unit 1 Receives 50 Percent of the Significant Radiation from the Heated Oven. (B) Unit 2 is Shielded by the Target; Unit 1 Receives 20 Percent of the Incident Radiation from the High-Intensity Lamp.

GEOMETRY OF VIEWING ARRANGEMENT

The actual contribution of background radiation to the detected energy is determined by the geometry of the viewing arrangement. That is, the position of the target and the sensing head with respect to significant background sources determines how much of the background radiation is actually reflected or transmitted into the instrument's optical system.

If the sensing head can be positioned to avoid the reflected or transmitted radiation, temperature measurement errors can be avoided as well.

Two examples of this are

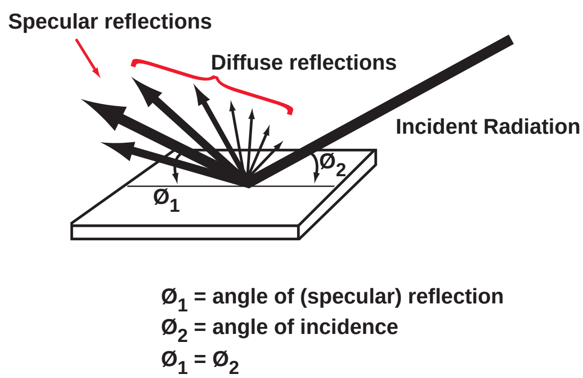


FIGURE 3

Specular Reflections Leave the Reflecting Surface at the Same Angle the Incident Radiation Makes when Striking the Surface. Diffuse Reflections, which Result from Roughness in the Surface, are Scattered in Other Directions.

shown in Figure 2. Both targets illustrated have some reflectivity but no transmittance, as is often the case in real applications.

For each example, the instrument in position 1 receives radiation with a component from the background and indicates a temperature that is too high. Each instrument in position 2 avoids reflections from the background source.

In Figure 2 (A), the unit in position 2 is simply aimed so that none of the background reflections enter its optical system. In Figure 2 (B), the unit in position 2 is shielded from the background radiation by the target itself, since it has no transmittance.

If this target had some transmittance at the detected wavelength, the sensing head could "see through" it to some extent. Then there would be less error if the instrument were aimed so that it looked through the target in the direction of a cooler background.

The kind of reflections depicted in Fig. 2 are specular reflections, for which the angle of incidence equals the angle of reflection. An uneven or rough surface can also produce diffused reflections (Fig. 3) which scatter some of the radiation in other directions. If the target material in Figure 2 (A) produces diffused reflections the brightness thermometer in location 2 is not completely safe from background reflections.

Because specular reflections are generally the most significant, however, they are the most important to avoid. Note that although the reflectivity may be different for the visible and infrared regions, it still may be possible to observe the direction of the reflected energy if the background source is incandescent.

If the background source is not hot enough to radiate at visible wavelengths, the angles of incidence and reflection must be visually estimated.

In some applications it is impossible to position the instrument so that it avoids background radiation. When this is the case, a final possible solution is to use some form of shielding to eliminate the problem.

An opaque shielding material that is appropriately placed between the background source and the target can be used to block the background radiation before it can be reflected off, or transmitted through, the target.

Of course, geometrical considerations are still important here, since it is necessary to know the path of potential reflections (or transmissions) in order to shield properly.

In particularly difficult situations, a cooled sight tube accessory can greatly improve the accuracy of temperature measurements. This tube is attached to the sensing head to provide an almost completely shielded view path.

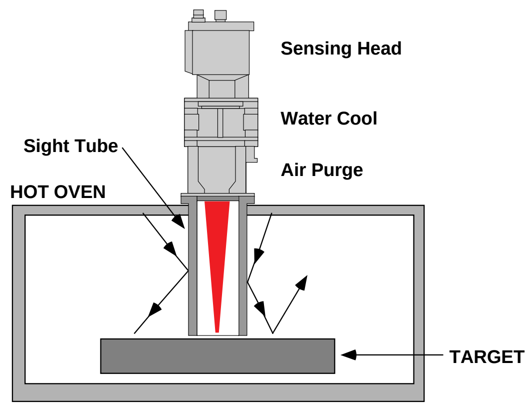


FIGURE 4

A Cooled Sight Tube Accessory can be used to Prevent Background Reflections from Entering the Optical System.

Reflections from the background that would have entered the optical system are blocked by the presence of the tube, as shown in Figure 4. It is imperative, however, that the sight tube be kept cooler than the target. Otherwise, the hot tube itself would emit a significant amount of radiation, defeating its shielding action.

There are also special infrared thermometer systems which can eliminate background interferences in some applications. These systems will use either a second infrared sensing head or thermocouple to measure the background.

PUTTING THE PIECES TOGETHER

Background interferences can get quite complex due to multiple reflections, multiple sources and the like. Other complications can arise when hot gases or sooty flames lie between the sensing head and the target. Then the hot molecules in the transmission path have the effect of both reducing and adding to the detected energy.

These molecules absorb or scatter some of the radiation emitted by the target, and emit a significant amount of radiation themselves.

Some applications, however, lend themselves to a relatively simple analysis. Although direct viewing into an oven is not recommended, it is an application that allows for a more rigorous examination of how error is produced.

To determine the effect of the background on the detected radiance, known conditions will be assumed. To arrive at actual numerical temperature error values requires a knowledge of precisely how radiance (which we will call N) depends on temperature.

Since this relationship, given by the Planck equation, involves mathematics beyond the scope of this chapter, the results will be translated into values, calculated in terms of radiance, that relate to temperature.

EXAMPLE: VIEWING INTO AN OVEN

A brightness thermometer is used to measure the temperature of a target which is contained within a heated oven. In order to accomplish this, the unit must be aimed directly into the oven.

The instrument responds to wavelengths of 2.0 to 2.6 µm, and the target has an emissivity of 0.75 and no transmittance in this spectral region: (a) If the target temperature is 700°F and the background temperature is 1,000°F, how much of the detected radiance is emitted by the background and how much of it is emitted by the target; and (b) what is the detected radiance if the target is removed from the oven and viewed in a much cooler environment?

Answer: (a)The total detected radiation is given by: (2)

$$N_{TOTAL} = N_{FROM\ TARGET} + N_{FROM\ BACKGROUND}$$

Because the target has an emissivity of 0.75, it radiates 75 percent of the energy that would be emitted by a blackbody at 700° F. So

$$N_{FROM\ TARGET} = N_{EMITTED} = 0.75\ N_{700}$$

It will be assumed that the oven is much larger than the target so that it approximates blackbody characteristics. The oven's radiance equals that of a blackbody at 1,000°F, or $N_{1,000}$.

Since the target is essentially surrounded by the oven walls, it is not possible to position the sensing head to avoid error. Radiation is reflected and/or transmitted in every direction according to the target's R and T characteristics. So the detected radiance from the background is given by: (3)

$$N_{FROM\ BACKGROUND} = N_{REFLECTED} + N_{TRANSMITTED} = RN_{1000} + \tau N_{1000}$$

Since the target has zero transmittance, we know from equation (1) that the reflectivity must equal 0.25. Substituting these values into equation (3) gives

$$N_{FROM\ BACKGROUND} = 0.25\ N_{1000}$$

Therefore equation (2) becomes: (4)

$$N_{TOTAL} = 0.75\ N_{700} + 0.25\ N_{1000}$$

(b) When the background's temperature is much lower than the target's, the contribution from the background becomes negligible. That is, the second term in equation (4) would be < 0.75 N_{700}, so we can say that the total detected radiation is just 0.75 N_{700}.

Table 1 shows that when the background is 1,000°F, there is an error of 169°F. Notice in the table that the error in this example diminishes quickly as the background temperature falls below the target temperature.

TABLE 1 BACKGROUND ERRORS (ΔT)

BRIGHTNESS THERMOMETER (2.0 to 2.6 μm)

$\varepsilon_{TARGET} = 0.75$, $T_{TARGET} = 700°F$

$T_{BACKGROUND}$ (°F)	($T_{INDICATED} - T_{TARGET}$) ΔT
400	1°
500	5°
600	15°
700	36°
800	69°
900	114°
1000	169°

MINIMIZING THE EFFECTS OF HOT BACKGROUND

Various methods of minimizing background errors have been mentioned throughout this section of the chapter. The following summarizes the most important points:

- Use a spectral region where the target emissivity is high.
- Avoid significant reflections (and transmissions) through position ing or shielding.

Although the general causes of background error have been considered, this discussion is by no means all inclusive. If you provide the IRCON sales engineers with the details of your application, these engineers can help you maintain the accuracy of your temperature measurements.

TEMPERATURE EFFECTS DUE TO INSTRUMENT CHARACTERISTICS CHAPTER 5

No measurement device produces perfect measurements because no real system is absolutely perfect. Manufacturers of infrared brightness thermometers, however, establish limits to the uncertainty involved in determining any given measurement. The instrument's measurement uncertainty specified by a manufacturer represents the worst case combination of various unavoidable built-in error sources.

In this final chapter, some of the more significant sources of instrument error will be analyzed. In addition, user guidelines will be provided so that the specified uncertainty range for a particular instrument is not exceeded.

INSTRUMENT ERROR SOURCES

CALIBRATION

The calibration of an infrared brightness thermometer involves adjusting the thermometer reading to match the temperature of a known blackbody standard source. There is an uncertainty associated with an operator's ability to make this adjustment. The limitation is imposed by the accuracy of the thermometer's temperature indications. For example, if the unit being calibrated had a meter scale like the one shown in Fig. 1, it would not be possible to ensure that the thermometer matched the blackbody temperature any more closely than approximately ±1°.

There is also calibration uncertainty associated with the blackbody standard's value. This has to do, in part, with how closely the standard approximates blackbody characteristics. Although a blackbody, by definition, radiates the ideal, maximum amount of energy possible at each temperature, no real object truly radiates ideally. It is possible, though, to make very good blackbody simulators (with emissivities very close to 1) using real materials shaped in the form of a cavity. Yet a margin of uncertainty remains, and its magnitude is determined by the design and construction of the blackbody used.

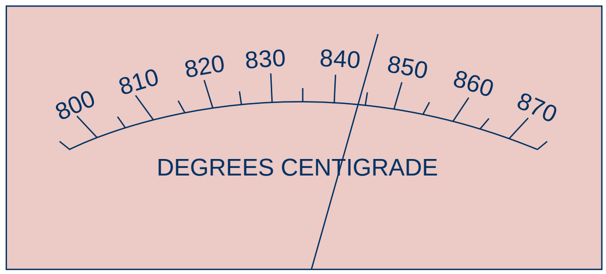


FIGURE 1
Temperature Values on this Meter Scale Cannot Be Read Better than Plus or Minus One Degree.

Not only is there some uncertainty about how much radiation the blackbody standard source is emitting at each temperature, there is also some question as to what the blackbody's temperature actually is. To know the blackbody temperature, we must have some other means of monitoring it. No matter what method is used, there is some degree of uncertainty associated with this measurement as well.

COMPONENT TEMPERATURE

Another uncertainty exists because the temperature of the infrared thermometer's components can affect these instruments' operation. Component temperature can alter not only the action of the sensor and the circuitry, but even the properties of filters and other optical components. These effects are especially important when the instrument is subjected to a wide range of temperatures. A unit that was calibrated with its outer case at room temperature will not produce the exact same measurements when positioned near a high-temperature furnace. Therefore, specific instrument precautions such as cooling, for example, must be taken to maintain instrument calibration.

ELECTRONICS

The electronics in infrared thermometers are used to process voltages generated by radiant energy striking the detector. Because brightness thermometers measure this voltage quantitatively to determine a target's temperature, the voltage levels cannot be allowed to drift or fluctuate arbitrarily. Any situation which allows this to occur produces an error.

Electrical noise, for instance, can produce significant fluctuations, especially if the signal is small. Either very fast response

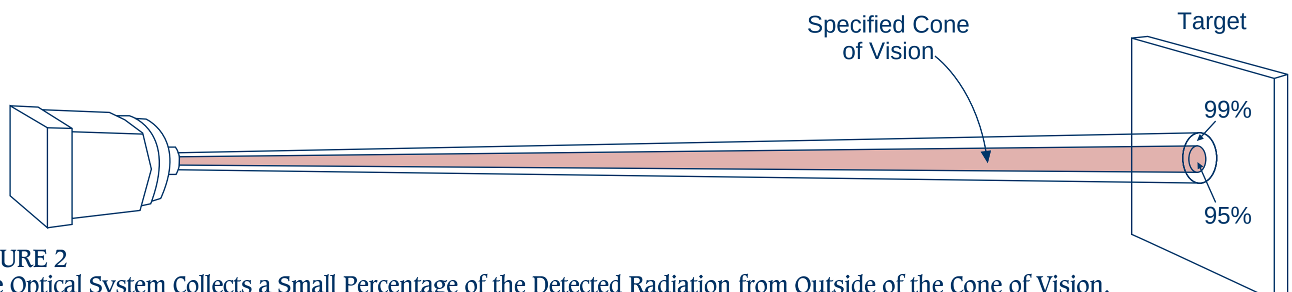


FIGURE 2
The Optical System Collects a Small Percentage of the Detected Radiation from Outside of the Cone of Vision. The Instrument's Sensitivity to Stray Radiation Decreases with Angle Outward from the Cone of Vision.

times or very low target temperatures can degrade the signal to noise ratio. Also, as electrical components age and are subjected to different environmental conditions, their circuit voltages have a tendency to drift. IRCON instruments are "burned in" using an environmental chamber to minimize this problem.

OPTICAL SYSTEM

The optical system focuses radiation from the target onto the detector. Because optical systems are high precision devices, errors introduced generally are quite small. Of these small optical errors, the most significant is usually related to the instrument's ability to reject radiation from outside its field of view – or its sensitivity to stray radiation.

We usually assume that the optical system collects only the radiation coming from the area on the target's surface which intersects the instrument's specified cone of vision. However, it is physically impossible to make an optical system which has an absolutely distinct cut-off to the area it measures. As a result, there is a relatively small percentage of contribution from sources outside the specified cone of vision. The contribution diminishes as the angle from the cone of vision increases (Fig. 2).

Optical system errors present very few problems when the target is much larger than the measuring area. When this is true, most of the detected radiation outside the specified cone of vision is emitted by the target object, as in Fig. 2. In this case, any error due to the instrument's sensitivity to stray radiation is negligible; the target itself is the source of most of the "stray" radiation.

On the other hand, if the spot size is about the same size as the target, much of this outside contribution comes from the background. If we assume that five percent of the detected radiation comes from outside the specified cone of vision, then as much as five percent of the detected radiation may come from the background. Yet if the target diameter is twice the specified spot size, only about one percent of the detected radiation comes from background sources. Reducing the contribution from background sources reduces any resulting measurement error.

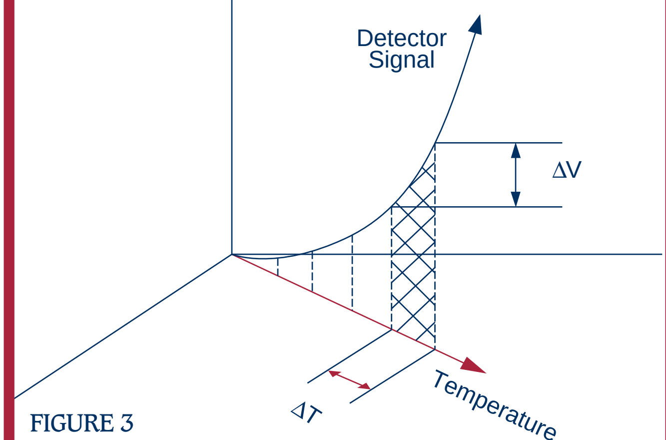


FIGURE 3

Linearization Relates Increasing Changes in the Detector Voltage (ΔV) to Constant Changes in Temperature (ΔT).

LINEARIZATION

The electronic signal in an infrared brightness thermometer is produced by radiant energy striking the detector. Because the target's radiance increases exponentially with temperature, so does the signal produced by the detector. In order to get temperature readings, the infrared thermometer must relate ever-increasing voltage changes (ΔV) with a unit temperature change (ΔT) as the target gets hotter. This signal processing, called linearization, may be thought of as the projection of the nonlinear detector signal onto a linear (straight line) temperature scale, as shown in Fig. 3.

In order to associate the right temperature change with a given change in detector signal, the instrument must know how the signal varies with temperature. The characteristics of a blackbody radiator define this universal reference function. Since linear circuits are the easiest and most reliable to work with, the usual method of electrically implementing this function is by using linear segments.

Figure 4 shows the slope increasing from one segment to another so that the blackbody radiance function is approximated. The effect of a fixed change in the signal voltage on the indicated temperature depends on the slope of its segment: the greater the slope, the smaller the temperature change.

Although the characteristics of this kind of linear circuit are very close to those of the true blackbody function, the linear function is only an approximation. In fact, it matches the true function exactly at only two points per segment, where the two graphs overlap. For every other detector voltage there is a small error in the indicated temperature due to linearization. It is important to realize, however, that the approximation is improved when more segments are used in the design. Then, not only is the approximation exactly right at more points, but the error is reduced everywhere else as well.

USER GUIDELINES

If an instrument is used properly, it will operate with an accuracy within its specified uncertainty. Note, though, that some instrument errors can worsen with time. Periodic maintenance checks are a vital means of verifying that an instrument is operating according to its specifications. There are other considerations which can be important in keeping the effects of some of the instrument error sources to a minimum.

COMPONENT TEMPERATURE

For applications where exact temperature measurements are critical, it is helpful to keep the unit's outer case temperature as close as possible to what it was during its last instrument calibration.

Also, be careful about relying on uncertainty specifications if the unit has not recently undergone a routine maintenance check. There is a chance that such a unit may be operating out of specifications if its case temperature is far from the center of the allowable case temperature range. An instrument operates least reliably when subjected to temperature extremes.

OPTICAL SYSTEM

If you are going to calibrate your own instrument, it is particularly important to be aware of the possible influence of stray radiation. Suppose the blackbody target used for calibration is exactly the same size as the reticle in the sighting telescope. Then any radiation detected from outside the specified field of view comes from the background.

Since the blackbody sources used in calibration usually are hotter than room temperature, the contribution from the background represents a much lower temperature than the blackbody temperature. Thus the average amount of detected radiation is lower than it should be, and an energy level that is too low will be associated with the blackbody temperature. This throws off the calibration and introduces an error into all subsequent measurements.

Clearly the error would be reduced if the blackbody target were larger than the reticle. It is considered good practice to calibrate an instrument using a blackbody target which is at least two times the reticle diameter. If this guideline is also followed for subsequent targets, sensitivity to stray radiation will not present a problem.

ELECTRONICS

Preventing electrical problems which result from poor installation techniques is possible. Since leads from the sensing head or to a controller can pick up noise from electromagnetic interferences, it is very important to follow the wiring guidelines presented in the IRCON operations manual. For instance:

- Always use shielded cables.
- Shield all low level outputs.
- Use a "clean" power line. Avoid power lines driving brush motors; loads driven by SCRs and contactors; and other intermittent, high in-rush loads which distort the power line waveform.
- Before connecting any device to an output, verify that the impedance values of the output and the input are compatible.
- Avoid ground loops between the sensing head, the signal processing unit, and remote indicator units.

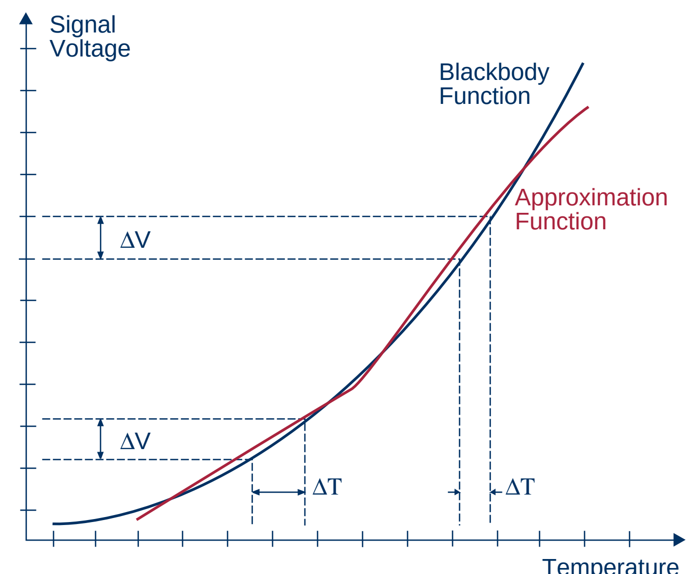


FIGURE 4

The Signal Voltages Produced by a Blackbody Radiator can be Approximated Using Straight Line Segments. A Smaller Temperature Change (ΔT) is Associated with the Voltage Change ΔV at Higher Temperatures Since the Slope of the Segments Increases.

MINIMIZING INSTRUMENT ERRORS

The magnitude of instrument errors is highly dependent on the specifics of the application. However, most instrument errors are subject to the same trends as emissivity and transmission errors.

For instance, suppose ambient temperature conditions cause a five percent increase in an instrument's signal voltage. This problem will cause more significant errors in units which detect longer wavelengths than in those which detect shorter wavelengths. Similarly, the temperature error increases as the target temperature increases. Thus, it is beneficial to choose the unit which measures the shortest wavelength possible for the desired temperature.

Instrument errors typically represent the least significant of all possible kinds of errors. Uncertainty about a target's emissivity value, for example, usually far outweighs any problems which occur due to linearization. Nevertheless, it makes sense to try to minimize all sources of error. As we have seen, the most practical ways to minimize instrument errors are:

- Install the instrument with care and always follow recommendations given in the operations manual.
- View target where it is at least twice the instrument spot size.
- Avoid extreme instrument case temperatures.
- Use a clean power line.
- Shield all signal wiring.
- Institute a routine maintenance schedule to guarantee continued reliability.

Remember, the best way to minimize all temperature measurement errors is by choosing the right instrument for your application.

WHEN TO USE TWO-COLOR IR THERMOMETERS
CHAPTER 6

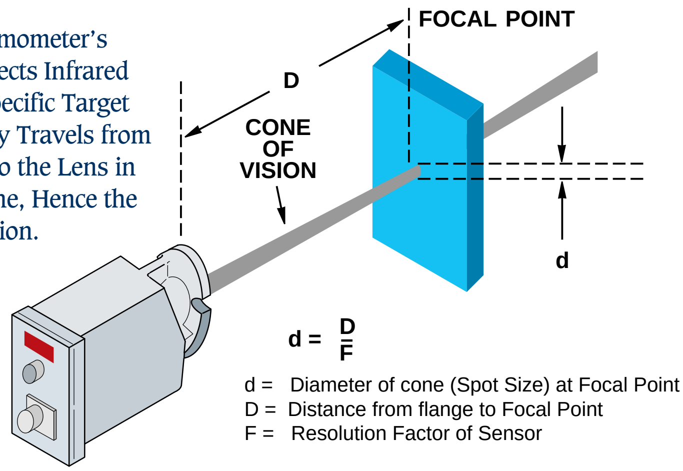
For most infrared thermometers to function properly, the hot object being measured must fill the target area and no obstruction can interfere with the cone of vision. When an infrared thermometer looks at a specific target, it measures intensity of radiant energy over an entire target area. The energy travels from the target back to the lens in the form of cone, hence the term cone of vision (Fig. 1).

Therefore, an infrared thermometer acts like a camera; if the lens is obstructed, with a finger for example, the resulting image will be underexposed on the film. Similarly, obstructions in the cone of vision will cause the thermometer to read incorrectly.

Problems which will cause an infrared thermometer to read incorrectly include:

1. Small objects (too small to fill the target area).
2. Dust, smoke or steam which obscure the line of sight.
3. Windows in the process get dirty and are difficult to keep clean.
4. Emissivity of the product changes (due to changes in alloy or surface condition).

FIGURE 1
An Infrared Thermometer's Lens System Collects Infrared Energy from a Specific Target Area. The Energy Travels from the Target Back to the Lens in the Form of a Cone, Hence the Term Cone of Vision.



A two-color or ratio thermometer can usually solve these problems. A brightness thermometer has to have a clear unobstructed view of a target (Fig. 2) whereas some obstructed targets can only be measured by using a two-color thermometer (Fig. 3).

A two-color thermometer consists of two brightness thermometer in the same package. By using two detectors, a two-color thermometer operates at two separate wavelengths while both see the same hot target simultaneously.

In basic terms, a two-color thermometer works properly as long as whatever affects one wavelength affects the other wavelength by the same amount. This indicates that the only reason the ratioed detector output changes is because of variances in temperature.

Every two-color thermometer has a limit as to how much signal can be lost. This is referred to as the reduction ratio. The reduction ratio can vary from as low as 5:1 to as high as 25:1. In other words, 96 percent of the signal could be lost and still read an accurate temperature. Also keep in mind that the loss in signal can come from three sources:

1. Low emissivity of the target.

FIGURE 2
To function Properly, a Brightness Thermometer Must Have an Unobstructed View of a Target.

FIGURE 3
The Only Way to Measure Some Obstructed Targets is by Using a Two-Color Thermometer.

2. Object too small to fill cone of vision.
3. Obstruction caused by smoke, steam, dirt or dirty windows.

If an object has an emissivity of 0.25, then 75 percent of the signal is lost, which means only about 10 percent more signal can be lost as a result of obstructions. When the reduction ratio limit is reached, the instrument can sense this and will indicate an "invalid" reading.

An invalid reading simply says the signal is so low that a repeatable result is not possible. Rather than indicate erroneous readings, the instrument is forced to a below zero scale output and provides an alarm of its inability to compute the temperature.

In some applications, adjustments must be made for non-gray emissivity variations. A good example is in the measurement of molten metals. Usually the metal will have a different emissivity for each wavelength. Therefore, when a two-color thermometer looks at the molten metal, the ratio or slope will be incorrect and an error will occur in the reading.

To compensate for these types of incorrect readings, all two-color thermometers have an emissivity correction, or E-slope feature. When viewing the molten metal, the E-slope control is turned until the instrument reads the correct temperature. The correct temperature is obtained by using a disposable thermocouple.

The E-slope control simply multiplies the measured ratio by an adjustable constant which corrects the instrument calibration for the unequal spectral emissivities of the target. Once the E-slope is set, the problems of smoke, steam, dust, among others, are handled by the instrument.

Similar errors will occur if an improper window material is used. Pyrex windows, for example, are slightly colored and transmit differently in the two spectral regions. Once again, the E-slope control can be used to correct this problem.

Two-color thermometers solve many application problems, but there are some factors which must be considered when using them to measure temperature. These factors include reflections, small targets, scale and physical characteristics of a target.

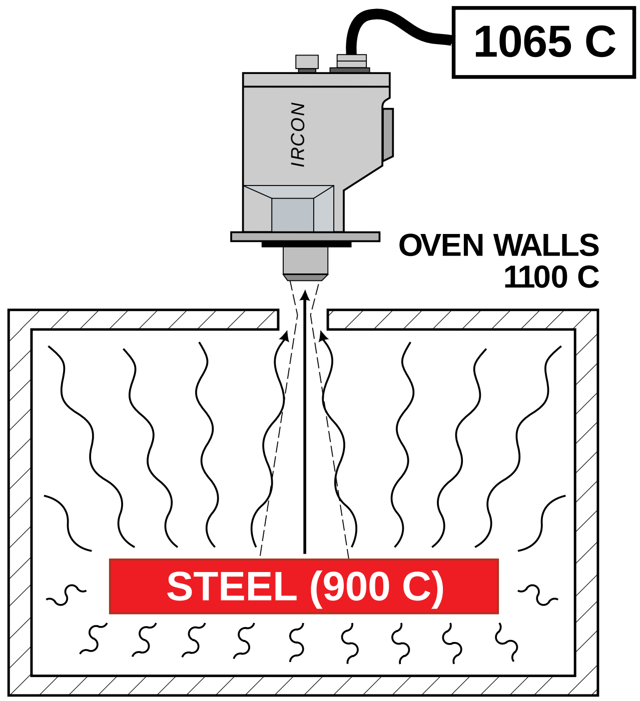


FIGURE 4

Two-Color Infrared Thermometers do not Solve Problems Caused by Reflected Energy. An Example of this Reflectance Occurs when the Walls of a Gas Fired Oven are Warmer than the Steel in the Oven.

REFLECTIONS

Two-color infrared thermometers do not solve the problems caused by reflected energy. For example, steel in a hot gas fired oven may be at 900° C and the oven walls could be at 1,100° C. This means the hot steel is completely surrounded by a source hotter than the steel (Fig. 4).

A two-color thermometer measures the composite radiant signals streaming from the billet surface for each spectral channel, computes the ratio of these two signals, and displays the temperature equivalent of this ratio. Unfortunately, but quite naturally, this indicated temperature is neither that of the steel nor of the background. Adjusting the E-slope will not correct this condition. The only way to correct reflection problems is to remove the interfering hot background.

SMALL TARGETS

As previously noted, the hot object does not have to fill the entire target area of the thermometer. Applications such as hot wires, hot rods and molten glass streams are usually very narrow and do not fill the field of view as seen in the telescope reticle. The problem that has to be considered is what fills the remainder of the reticle. If the remainder is filled with another hot object, averaging the two objects may possibly cause an incorrect reading. If the background around the wire or rod is cool, the background contribution to the two target signals and the resulting ratio will be negligible, indicating a correct temperature.

THICK OXIDE

Many two-color thermometers are used in steel mills. A popular misconception in the industry is that a two-color thermometer can see through scale. Unfortunately, that is not true.

Cold scale which fills the entire reticle will simply cause the instrument to read a low temperature. Usually the scale is somewhat cooler than the steel but not significantly cooler. The instrument will average the reading, providing a low read out. Measuring the steel where the scale has been removed is the best way to compensate for this.

PHYSICAL CHARACTERISTICS

A two-color thermometer is a sophisticated sensing head. There are many special features required to ensure the instrument reads the proper temperature. An achromatic lens and thru-the-lens optics are two special features associated with a two-color thermometer.

It is important for two-color thermometers to have an achromatic lens. This means a lens that has the ability to focus both wavelengths on the focal plane. If two different wavelengths of energy travel through a lens, they will each bend differently. The longer wavelength does not bend as much as the short wavelength. An achromatic lens corrects this problem by ensuring that the two wavelengths focus the image of the target on the detector plane.

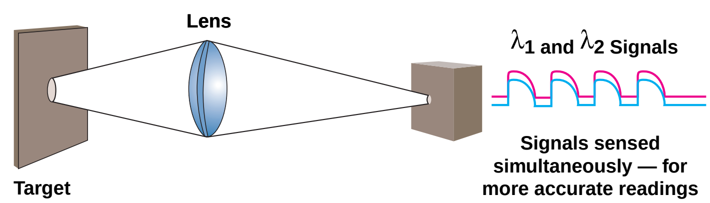
Another special feature associated with two-color thermometers is thru-the-lens optics. This feature provides an operator with the ability to look through an eyepiece at the back of the sensing head and see the hot target. This allows the eye to actually see the area the detector is measuring.

Two-color thermometers require either two detectors at two wavelengths or one detector that works with two filters to obtain two separate signals.

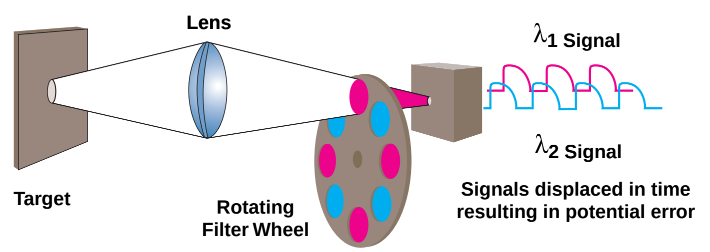
TWO- COLOR TECHNIQUE

The IRCON dual detector measuring technique (A)overwhelmingly provides faster and more accurate temperature measurement in comparison to instruments that use the filter wheel technique (B). In the IRCON two-color scheme, ratio computation of the two spectral signals takes place simultaneously. In the filter wheel scheme, ratio computation is displaced in time resulting in slower operation and potential error. Superior temperature measurement under dynamic target conditions (target moving in and out of the field of view or temperature fluctuations) is made possible because both detectors view and measure the same spot on the target at the same instant.

A The two-color technique using two detectors measures simultaneously, allowing accurate readings and fast response time.



B Filter wheel technique using one detector is time-delayed, resulting in potential error and slow response time.



Should you require any assistance or further explanation, please call our Application Engineering Department, toll free in the U.S. and Canada at 1-800-323-7660.

APPLICATION WAVELENGTH SELECTION GUIDE

TYPICAL APPLICATIONS	WAVELENGTH (µm) 0.65	0.9	1.0	0.7-1.08 &1.08 RATIO	1.55 &1.68 RATIO	1.65	2.0	3.43	3.9	5.0	7.9	8-14
ALUMINUM			•		•	•	•					
ASPHALT										•	•	
AUTOMOTIVE		•	•	•	•	•	•	•			•	•
APPLIANCES							•	•			•	•
AMMUNITION							•	•				•
BATTERIES							•					•
CEMENT	•	•	•	•			•		•		•	•
CONSTRUCTION MATERIALS							•			•	•	
PHARMACEUTICAL											•	
FIBERGLASS	•		•	•			•	•		•		•
FOOD PROCESSING							•	•				•
FOUNDRY	•	•	•	•			•					
GLASS - MELTING	•	•	•	•								
GLASS - FLAT										•		
GLASS BOTTLES/ CONTAINERS		•								•	•	
HEAT TREATING		•		•	•	•		•				
INDUCTION HEATING		•		•	•	•		•				
KILNS	•	•		•			•		•	•		•
METAL WORKING		•		•	•	•		•				
MINING				•								
NON-FERROUS METALS			•		•	•		•				
OVENS		•	•	•	•	•	•	•	•	•	•	•
PAPER							•			•	•	
PLASTICS							•			•	•	
RUBBER							•			•	•	
SEMICONDUCTORS		•	•	•	•		•		•	•		
STEEL	•		•	•		•		•		•		
TEXTILES							•	•			•	•
UTILITIES				•							•	

To determine the IRCON instrument that is most appropriate for your application needs, please refer to the latest edition of our Product Selection Guide brochure, part number 010128.

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In business since 1962, IRCON products perform with accuracy and repeatability in the harshest and most volatile conditions requiring precise temperature measurement and control.

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