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TRANSACTIONS

IN MEASUREMENT AND CONTROL

VOLUME I, 2ND EDITION

NON-CONTACT TEMPERATURE MEASUREMENT

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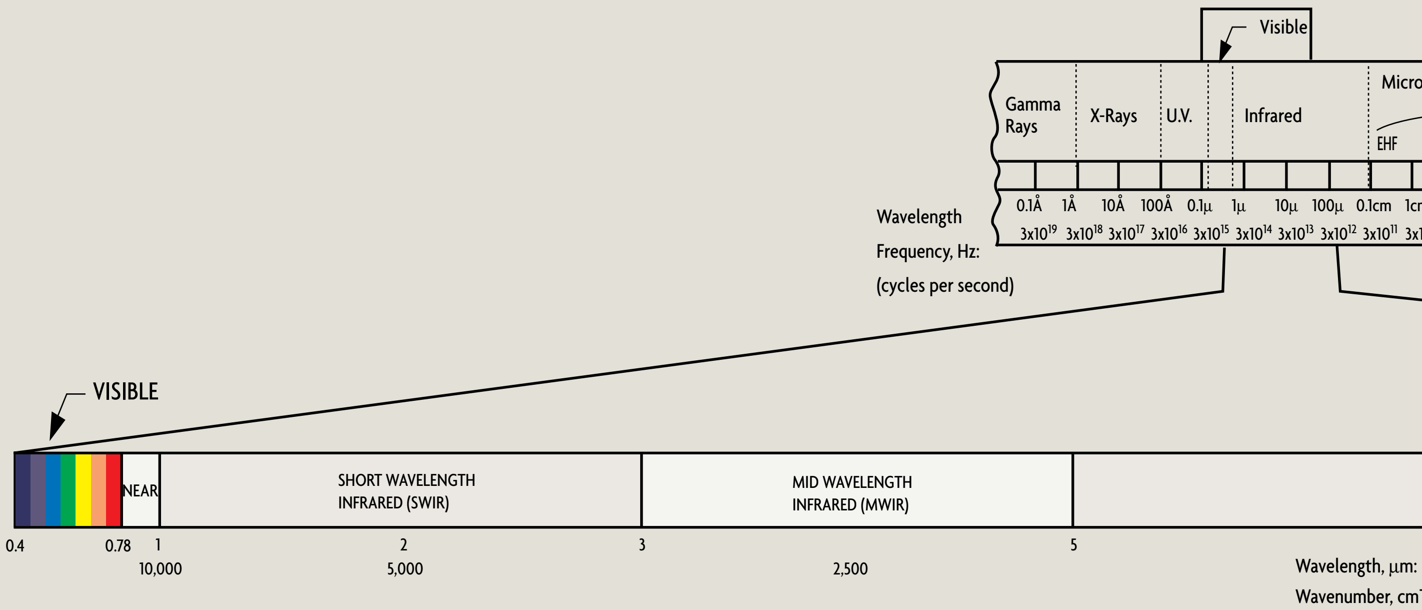

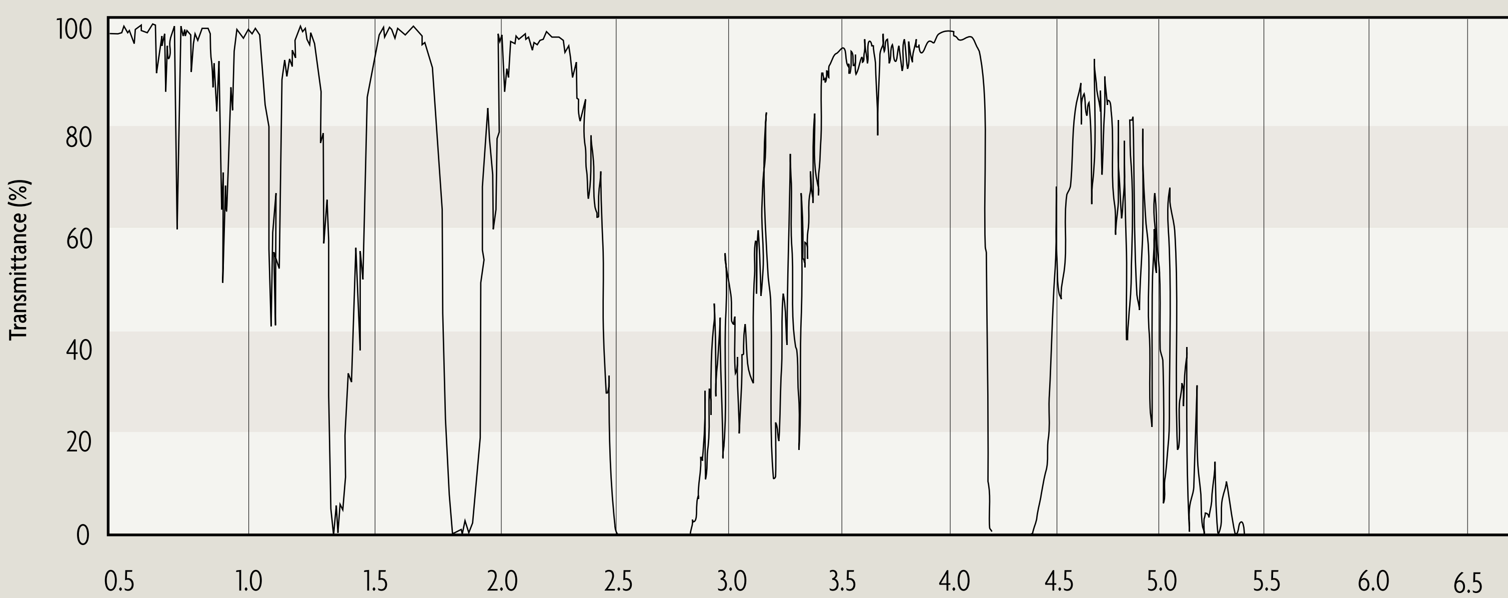

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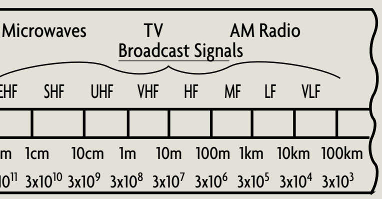

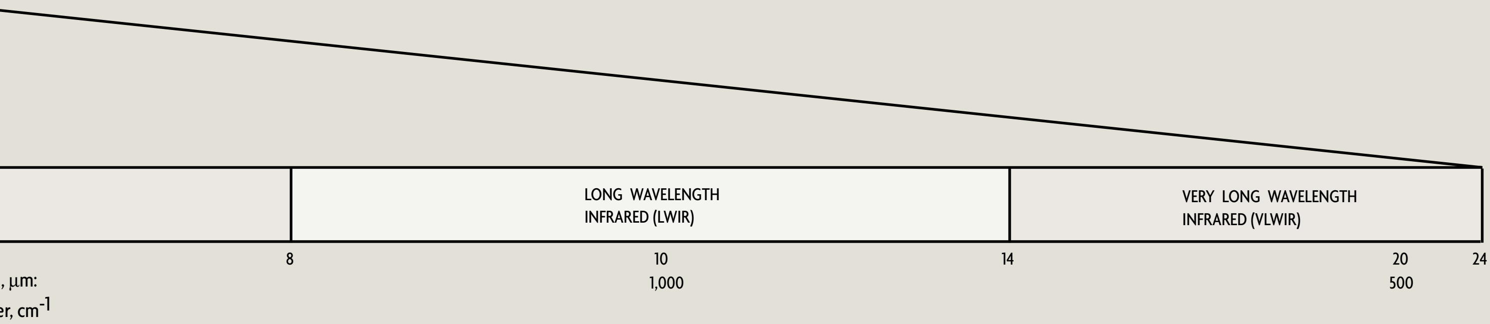

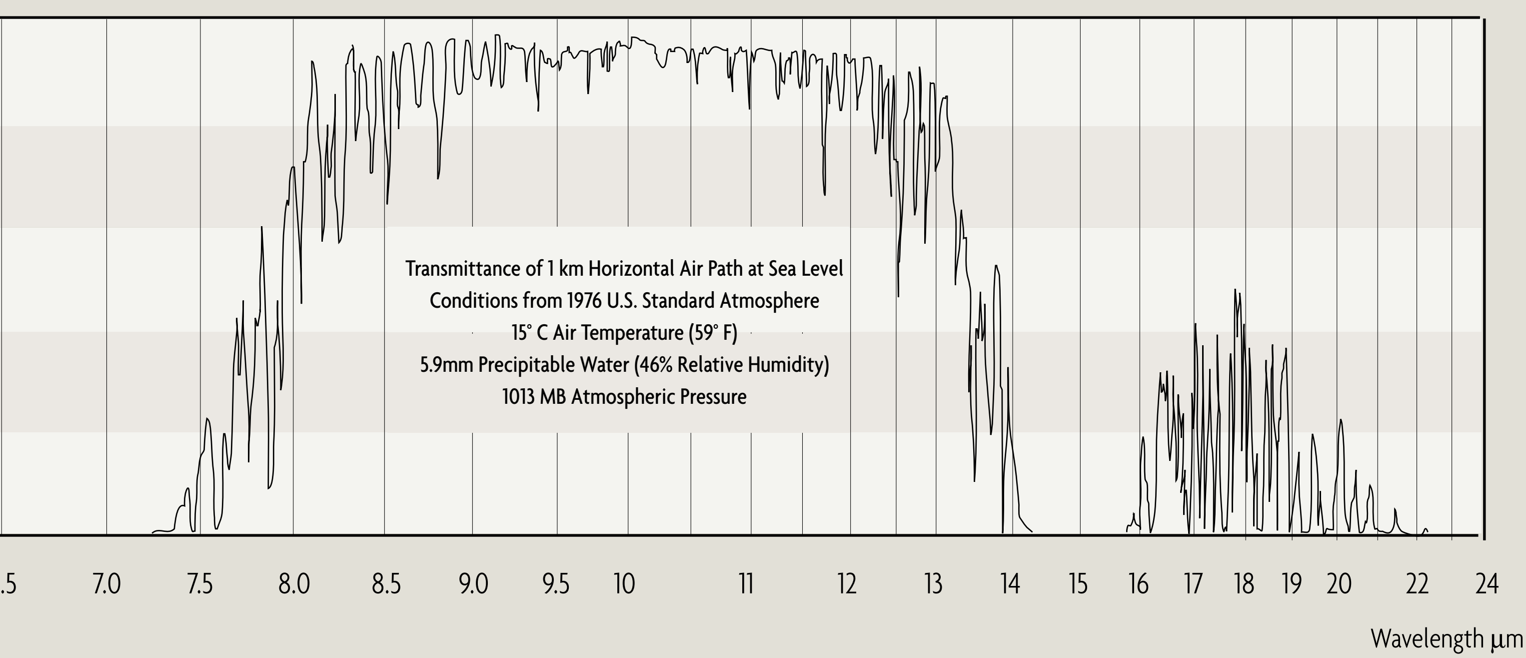

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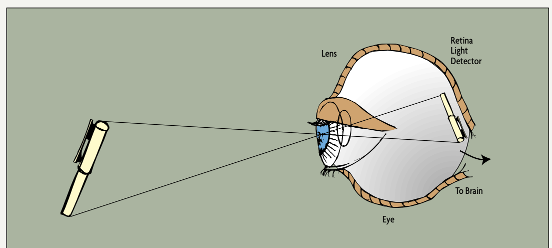

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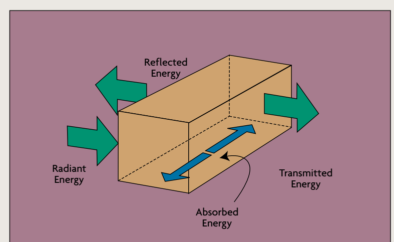

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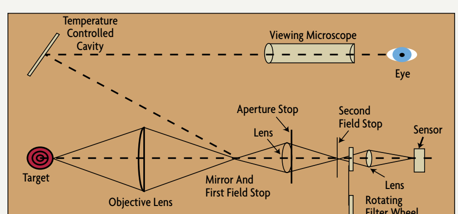

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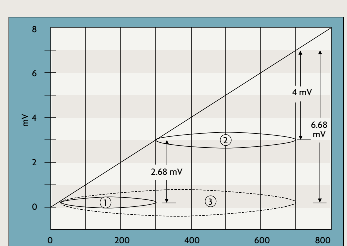

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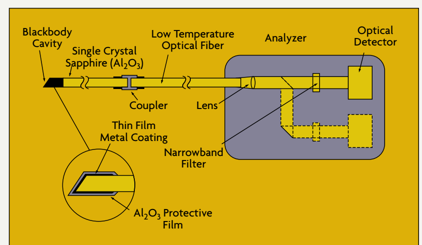

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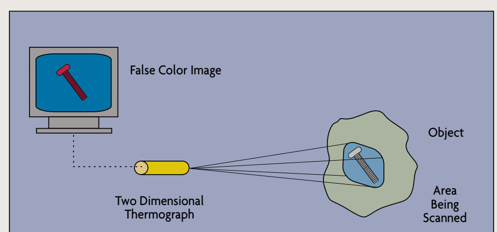

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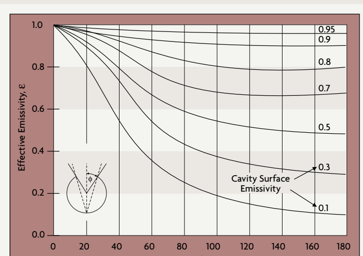

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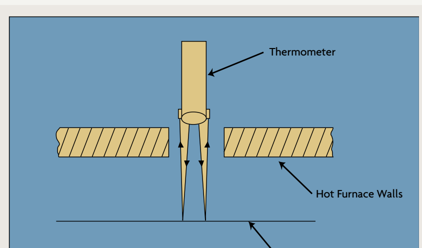

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A Historical Perspective

Our eyes only see the tiny fraction of energy emitted by the sun in the form of visible light. However, if we could see the infrared rays emitted by all bodies—organic and inorganic—we could effectively see in the dark. Though invisible to the human eye, infrared radiation can be detected as a feeling of warmth on the skin, and even objects that are colder than ambient temperature radiate infrared energy. Some animals such as rattlesnakes, have small infrared temperature sensors located under each eye which can sense the amount of heat being given off by a body. These sensors help them to locate prey and protect themselves from predators.

Non-contact temperature sensors use the concept of infrared radiant energy to measure the temperature of objects from a distance. After determining the wavelength of the energy being emitted by an object, the sensor can use integrated equations that take into account the body's material and surface qualities to determine its temperature. In this chapter, we will focus on the history of radiation thermometry and the development of non-contact temperature sensors.

IR Through the Ages

Although not apparent, radiation thermometry has been practiced for thousands of years. The first practical infrared thermometer was the human eye (Figure 1-1). The human eye contains a lens which focuses emitted radiation onto the retina. The retina is stimulated by the radiation and sends a signal to the brain, which serves as the indicator of the radiation. If properly calibrated based on experience, the brain can convert this signal to a measure of temperature.

People have been using infrared heat to practical advantage for thousands of years. There is proof from clay tablets and pottery dating back thousands of years that the sun was used to increase the temperature of materials in order to produce molds for construction. Pyramids were built from approximately 2700-2200 B.C. of sun-dried bricks. The Egyptians also made metal tools such as saws, cutting tools, and wedges, which were crafted by the experienced craftsmen of their time. The craftsmen had to know how hot to make the metal before they could form it. This was most likely performed based on experience of the color of the iron.

Because fuel for firing was scarce, builders of Biblical times had to depend on the sun's infrared radiation to dry the bricks for their temples and pyramids. The Mesopotamian remains of the Tower of Babel indicate that it

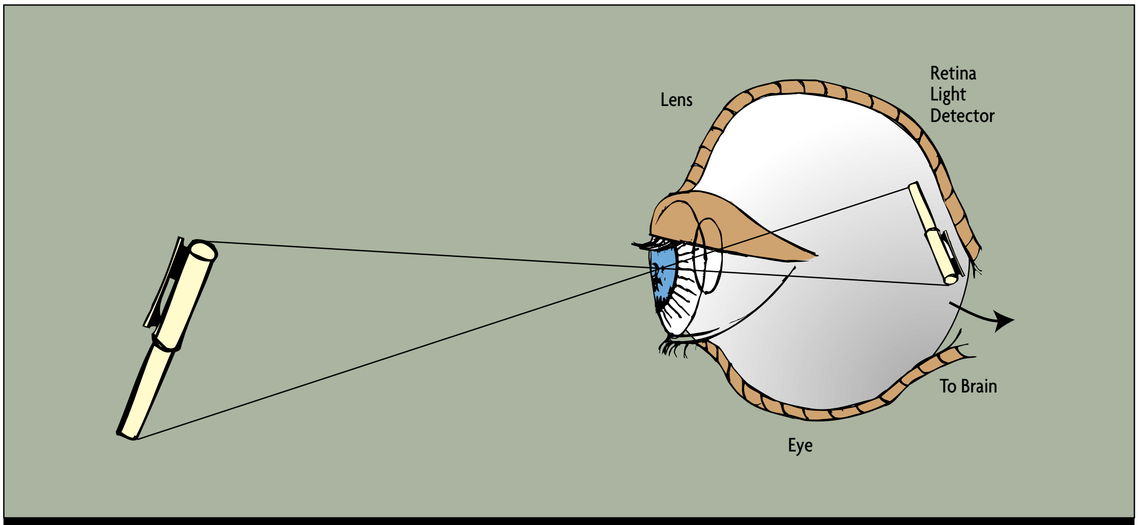

Figure 1-1: The First IR Thermometer

was made of sun-dried brick, faced with burnt brick and stone. In India, a sewer system dating back to 2500 B.C. carried wastewater through pottery pipes into covered brick drains along the street and discharged from these into brick culverts leading into a stream.

In ancient Greece, as far back as 2100 B.C., Minoan artisans produced things such as vases, statues, textiles. By using sight, they could approximate when a piece of material could be shaped. Terra-cotta pipes were built by heating them to a certain temperature and casting them into a mold.

In more recent years, special craftsmen have relied on their own senses to visualize when a material is the correct temperature for molding or cutting. Sight has been used for steel working, glass working, wax molding, and pottery. From experience, skilled craftsmen learned to estimate the degree of heat required in the kiln, smelter, or glass furnace by the color of the interior of the heating chamber. Just as a classical blacksmith, for example, might judge the malleability of a horseshoe by its cherry-red color.

In countries around the world, the technique of sight is still being used. In Europe, glass molding craftsmen use sight to determine when glass is ready to be shaped (Figure 1-2). They put a large piece of glass in a heating furnace by use of a large metal rod. When the glass reaches the desired color and brightness, they pull it out of the oven and immediately form it into the shape they want. If the glass cools and loses the desired color or brightness, they put it back in the oven or dispose of it. The glass makers know when the glass is ready, by sight. If you have a chandelier made of glass, or hand-made glasses from Europe, most likely they were formed in this way.


Figure 1-2: Glass Manufacture Using Visual IR Temperature Measurement

From Newton to Einstein

The thermometer was invented in Italy by Galileo Galilei (1564-1642), about two hundred years before the infrared light itself was discovered in 1800, and about 100 years before the great English scientist Sir Isaac Newton (1642-1727) investigated the nature of light by experimentation with prisms.

As published in *Opticks* in 1704, Newton used glass prisms to show that white light could be split up into a range of colors (Figure 1-3). The least bent portion of the light consisted of red, and then following in order, orange, yellow, green, blue, indigo, and violet, each merging gradually into the next. Newton also show that the different colors could be fed back through another prism to produce white light again. Newton's work made it clear that color was an inherent property of light and that white light was a mixture of different colors. Matter affected color only by absorbing some kinds of light and transmitting or reflecting others.

It was also Newton who, in 1675, proposed that light was made up of small particles, or "corpuscles." With this theory, Newton set out to measure the relative sizes of these corpuscles. From observations of the eclipses of the moons of Jupiter, Newton realized that all light traveled at the same speed. Based on this observation, Newton determined the relative sizes of the different color light particles by the refraction angles.

In 1678, Christiaan Huygens (1629-1695), a mathematician, astronomer, and natural scientist, challenged Newton's "corpuscular" theory proposing that light could be better understood as consisting of waves. Through the 1800s, the theory was well accepted, and it eventually became important in James Clerk Maxwell's theory of electromagnetic radiation.

Ironically for the field of infrared

thermometry, infrared radiation was first discovered by using a conventional thermometer. Friedrick William Herschel (1738-1822), a scientist and astronomer, is known as the father of sidereal astronomy. He studied the planets and was the first scientist to fully describe the Milky Way galaxy. He also contributed to the study of the solar system and the nature of solar radiation. In 1800, England, he was experimenting with sunlight. While using colored glasses to look at the Sun, Herschel noticed that the sensation of heat was not correlated to visible light (Figure 1-4). This led him to make experiments using mercury thermometers and glass prisms and to correctly hypothesize the existence of the invisible infrared heat waves. Until Herschel, no one had thought to put a thermometer and a prism together to try to measure the amount of heat in each color.

In 1800, Herschel had formed a sunlight spectrum and tested different parts of it with a thermometer to see if some colors delivered more heat than others. He found that the temperature rose as he moved toward the red end of the spectrum, and it seemed sensible to move the thermometer just past the red end in order to watch the heating effect disappear. It did not. Instead, the temperature rose higher than ever at a spot beyond the red end of the spectrum (Figure 1-4). The region was called infrared, which means "below the red."

How to interpret the region was not readily apparent. The first impression was that the sun delivered heat rays as well as light rays and that heat rays refracted to a lesser extent than light rays. A half-century passed before it was established that infrared radiation had all the properties of light waves except that it didn't affect the retina of the eye in such a way as to produce a sensation of light.

The German physicist Joseph von Fraunhofer (1787-1826) investigated the solar spectrum in the early 1800s. His spectroscope introduced parallel rays of white light by passing sunlight through a slit. The light contacted a prism, where the prism broke the light into its constituent rays. He produced an innumerable amount of lines, each an image of the slit and each containing a very narrow band of wavelengths. Some wavelengths were missing however. The slit images at those wavelengths were dark. The result was that the solar spectrum was crossed by dark lines. These lines would later become important to the study of emission and radiation.

In 1864, James Clerk Maxwell (1831-1879) brought forth for the first time the equations which comprise the basic laws of electromagnetism. They show how an electric charge radiates waves through space at various definite frequencies that determine the charge's place in the electromagnetic spectrum—now understood to include radio waves, microwaves, infrared waves, ultraviolet waves, X-rays, and gamma rays.

In addition, Maxwell's equations' most profound consequence was a theoretical derivation of the speed of electricity—300,000 km/sec.—extremely close to the experimentally derived speed of light. Maxwell observed and wrote, "The velocity is

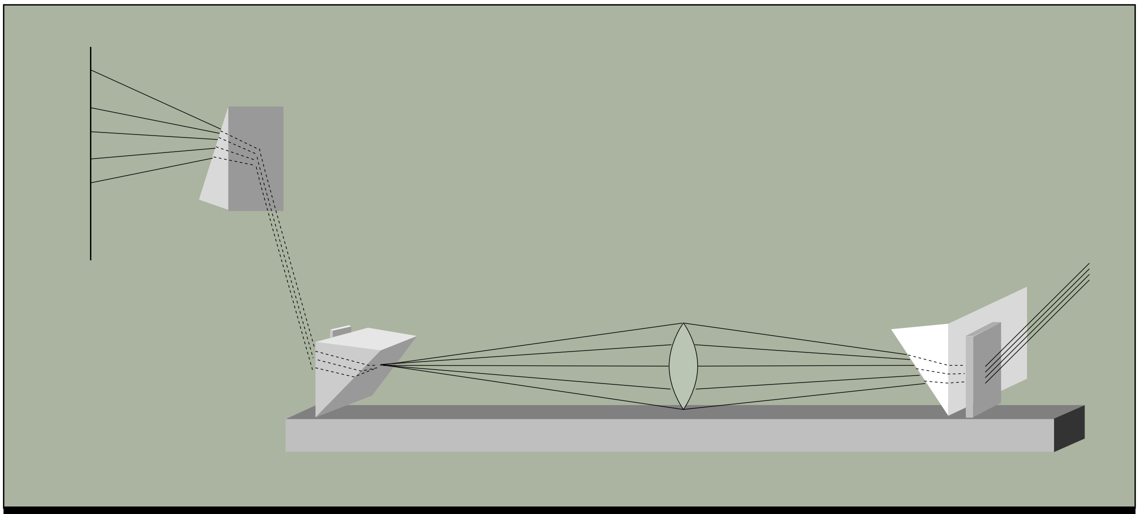

Figure 1-3: Newton Splits, Recombines White Light

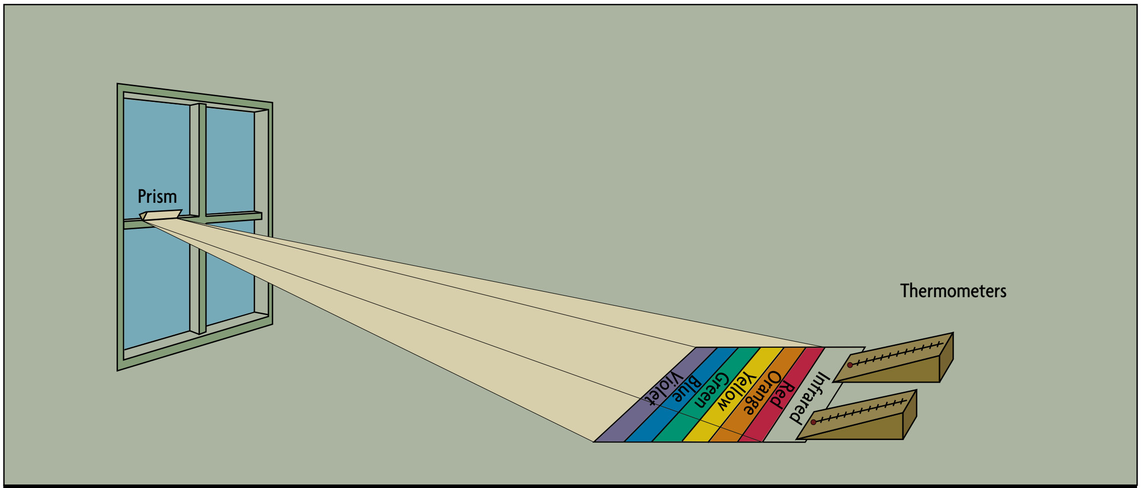

Figure 1-4: Herschel Discovers Infrared Light

so nearly that of light, that it seems we have strong reason to conclude that light itself...is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws." Maxwell was able to predict the entire electromagnetic spectrum.

Another German, physiologist and physicist Hermann von Helmholtz (1821-1894), accepted Maxwell's theory of electromagnetism, recognizing that the implication was a particle theory of electrical phenomena. "If we accept the hypothesis that the elementary substances [elements] are composed of atoms," stated Helmholtz in 1881, "we cannot avoid concluding that electricity, also, positive as well as negative, is divided into elementary portions which behave like atoms of electricity."

Gustav Robert Kirchhoff (1824-1887), a physicist and mathematician, worked with Robert Bunsen (1811-1899), an inorganic chemist and a physicist, in 1859 on a spectrometer that contained more than one prism. The spectroscope permitted greater separation of the spectral lines than could be obtained by Fraunhofer's spectroscope. They were able to prove that each chemical element emits a characteristic spectrum of light that can be viewed, recorded, and measured. The realization that bright lines in the emission spectra of the elements exactly coincided in wavelength with the dark lines in the solar spectrum indicated that the same elements that were emitting light on earth were absorbing light in the sun. As a consequence of this work, in 1859, Kirchhoff developed a general theory of emission and radiation known as Kirchhoff's law. Simply put, it states that a substance's capacity to emit light is equivalent to its ability to absorb it at the same temperature.

The following year, Kirchhoff, set forth the concept of a blackbody. This was one of the results of Kirchhoff's law of radiation. A blackbody is defined as any object that absorbs all frequencies of radiation when heated and then gives off all frequencies when cooled. This development was fundamental to the development of radiation thermometry. The blackbody problem arose because of the observation that when heating an iron rod, for example, it gives off heat and light. Its radiation may be at first invisible, or infrared, however it then becomes visible and red-hot. Eventually it turns white hot, which indicates that it is emitting all colors of the spectrum. The spectral radiation, which depends only on the temperature to which the body is heated and not on the material of which it is made, could not be predicted by classical physics. Kirchhoff recognized that "it is a highly important task to find this universal function." Because of its general importance to the understanding of energy, the blackbody problem eventually found a solution.

An Austrian physicist, Josef Stefan (1835-1893) first determined the relation between the amount of energy radiated by a body and its temperature. He was particularly interested in how hot bodies cooled and how much radiation they emitted. He studied hot bodies over a considerable range of temperatures, and in 1879 determined from experimental evidence that the total radiation emitted by a blackbody varies as the fourth power of its absolute temperature (Stefan's law). In 1884, one of his former students, Ludwig Boltzmann (1844-1906), determined a theoretical derivation for Stefan's experimentally derived law of blackbody radiation based on thermodynamic principles and Maxwell's electromagnetic theory. The law, now known as the Stefan-Boltzmann fourth-power law, forms the basis for radiation thermometry. It was with this equation that Stefan was able to make the first accurate determination of the surface temperature of the sun, a value of approximately 11,000°F (6,000°C).

The next quandary faced by these early scientists was the nature of the thermal radiation emitted by blackbodies. The problem was challenging because blackbodies did not give off heat in the way the scientists had predicted. The theoretical relationship between the spectral radiance of a blackbody and its thermodynamic temperature was not established until late in the nineteenth century.

Among the theories proposed to explain this inconsistency was one by the German physicist Wilhelm Wien and the English physicist John Rayleigh. Wilhelm Wien (1864-1928) measured the wavelength distribution of blackbody radiation in 1893. A plot of the radiation versus the wavelength resulted in a series of curves at different temperatures. With this plot, he was able to show that the peak value of wavelength varies proportionally with the amount of energy, and inversely with absolute temperature. As the temperature increases, not only does the total amount of radiation increase, in line with Stefan's findings, but the peak wavelength decreases and the color of the emitted light changes from red to orange to yellow to white.

Wien attempted to formulate an empirical equation to fit this relationship. The complex equation worked well for high frequency blackbody radiation (short wavelengths), but not for low frequency radiation (long wavelengths). Rayleigh's theory was satisfactory for low frequency radiation.

In the mid-1890s, Max Karl Ernst Ludwig Planck (1858-1947), a German physicist and a former student of Kirchhoff, and a group of Berlin physicists were investigating the light spectrum emitted by a blackbody. Because the spectrometer emitted distinct lines of light, rather than broad bands, they hypothesized that minute structures were emitting the light and began to develop an atomic theory that could account for spectral lines.

This was of interest to Planck because in 1859 Kirchhoff had discovered that the quality of heat radiated and absorbed by a blackbody at all frequencies reached an equilibrium that only depended on temperature and not on the nature of the object itself. But at any given temperature, light emitted from a heated cavity—a furnace, for example—runs the gamut of spectral colors. Classical physics could not predict this spectrum.

After several false starts, beginning in 1897, Planck succeeded in finding a formula predicting blackbody radiation. Planck was able to arrive at a formula that represented the observed energy of the radiation at any given wavelength and temperature. He gave the underlying notion that light and heat were not emitted in a steady stream. Rather, energy is radiated in discrete units, or bundles. Planck discovered a universal constant, "Planck's constant," which was founded on physical theory and could be used to compute the observed spectrum. This assumed that energy consisted of the sum of discrete units of energy he called quanta, and that the energy emitted, E, by each quantum is given by the equation $E = h\upsilon = hc/\lambda$, where υ (sec^{-1}) is the frequency of the radiation and h is Planck's constant—now

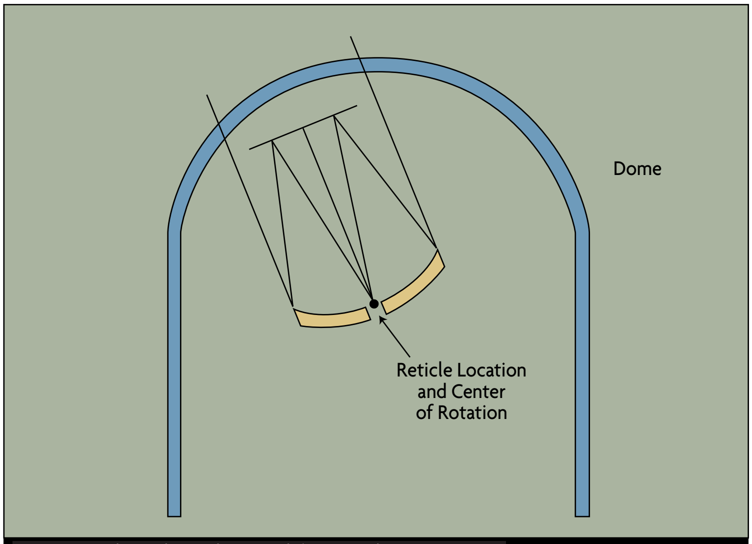

Figure 1-5: The Sidewinder Missile's IR Guidance System

known to be a fundamental constant of nature. By thus directly relating the energy of radiation to its frequency, an explanation was found for the observation that higher energy radiation has a higher frequency distribution. Planck's finding marked a new era in physics.

Before Planck's studies, heat was considered to be a fluid composed of repulsive particles capable of combining chemically with material atoms. In this theory, the particles of heat entered a system and moved between the particles. A mutual repulsion of the particles of heat created a pressure. A thermometer detected this pressure. Planck's constant became known as a "fortunate guess." It allowed for theoretical equations which agreed with the observable range of spectral phenomena, and was fundamental in the theory of blackbody radiation.

Albert Einstein (1879-1955) studied the works of Maxwell and Helmholtz. In 1905, Einstein used the quantum as a theoretical tool to explain the photoelectric effect, showing how light can sometimes act as a stream of particles. He published three papers in volume XVII of *Annalen der Physik.* In one, he set forth his now famous theory of relativity, but another showed that a fundamental process in nature is at work in the mathematical equation which had resolved the problem of blackbody radiation.

Light, Einstein showed, is a stream of particles with a computable amount of energy using Planck's constant. Within a decade, this prediction confirmed experimentally for visible light.

Max Karl Ernst Ludwig Planck initiated quantum theory at the turn of the twentieth century and changed the fundamental framework of physics. Wrote Einstein, "He has given one of the most powerful of all impulses to the progress of science."

Today's Applications

The first patent for a total radiation thermometer was granted in 1901. The instrument used a thermoelectric sensor; it had an electrical output signal and was capable of unattended operation. In 1931, the first commercially-available total radiation thermometers were introduced. These devices were widely used throughout industry to record and control industrial processes. They are still used today, but mainly used for low temperature applications.

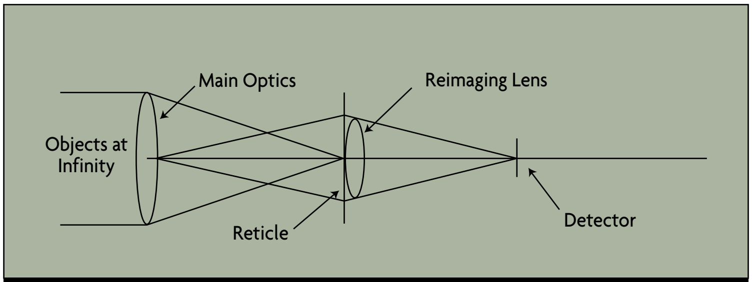

Figure 1-6: IR Optics for Missile Guidance

The first modern radiation thermometers were not available until after the second World War. Originally developed for military use, lead sulfide photodetectors were the first infrared quantum detectors to be widely used in industrial radiation thermometry. Other types of quantum detectors also have been developed for military applications and are now widely applied in industrial radiation thermometry. Many infrared radiation thermometers use thermopile detectors sensitive to a broad radiation spectrum and are extensively used in process control instrumentation.

Infrared thermometers currently are being used in a wide range of industrial and laboratory temperature control applications. By using non-contact temperature sensors, objects that are difficult to reach due to extreme environmental conditions can be monitored. They can also be used for products that cannot be contaminated by a contact sensor, such as in the glass, chemical, pharmaceutical, and food industries. Non-contact sensors can be used when materials are hot, moving, or inaccessible, or when materials cannot be damaged, scratched, or torn by a contact thermometer.

Typical industries in which non-contact sensors are used include utilities, chemical processing, pharmaceutical, automotive, food processing, plastics, medical, glass, pulp and paper, construction materials, and metals. Industrially, they are used in manufacturing, quality control, and maintenance and have helped companies increase productivity, reduce energy consumption, and improve product quality.

Some applications of radiation thermometry include the heat treating, forming, tempering, and annealing of glass; the casting, rolling, forging, and heat treating of metals; quality control in the food and pulp and paper industry; the extrusion, lamination, and drying of plastics, paper, and rubber; and in the curing process of resins, adhesives, and paints.

Non-contact temperature sensors have been used and will continue to be valuable for research in military, medical, industrial, meteorological, ecological, forestry, agriculture, and chemical applications.

Weather satellites use infrared imaging devices to map cloud patterns and provide the imagery seen in many weather reports. Radiation thermometry can reveal the temperature of the earth's surface even through cloud cover.

Infrared imaging devices also are used for thermography, or thermal imaging. In the practice of medicine, for example, thermography has been used for the early detection of breast cancer and for the location of the cause of circulatory deficiencies. In most of these applications, the underlying principle is that pathology produces local heating and inflammation which can be found with an infrared imager. Other diagnostic applications of infrared thermography range from back problems to sinus obstructions.

Edge burning forest fires have been located using airborne infrared imagers. Typically, the longer wavelengths of the emitted infrared radiation penetrate the smoke better than the visible wavelengths, so the edges of the fire are better delineated.

On the research front, one sophisticated infrared thermometry application is in the study of faults in metals, composites, and at coating interfaces. This technique is known as pulsed video thermography. A composite material consisting of a carbon-fiber skin bonded to an aluminum honeycomb is subjected to pulses of heat from a xenon flash tube. Infrared cameras record a frame-by-frame sequence of heat diffusion through the object, which is displayed on screen. Defects show up as deviations in the expected patterns for the material being tested.

Among the military applications of radiation thermometry are night-vision and the "heat-seeking" missile. In the latter case, the operator simply launches the missile in the general direction of the target. On-board detectors enable the missile to locate the target by tracking the heat back to the source. The most widely known military infrared missile applications are the Sidewinder air-to-air missile and a satellite-borne intercontinental ballistic missile (ICBM) detection system.

Both rely on detecting the infrared signature of an emission plume or very hot exhaust engine. The Sidewinder missile guidance system is shown schematically in Figure 1-5. A special infrared dome protects the optical system inside. The optical system consists of a primary and secondary mirror and a set of correction lenses to cause an image to focus onto a special reticle. All the light from the reticle is focused onto a detector (Figure 1-6). The reticle can modulate the radiation to distinguish between clouds and provide directional information.

Portable surface-to-air missiles, SAMs, are effective defense units that guide themselves to a target by detecting and tracking the heat emitted by an aircraft, particularly the engine exhaust. T

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Theoretical Development

All matter—animate or inanimate, liquid, solid, or gas—constantly exchanges thermal energy in the form of electromagnetic radiation with its surroundings. If there is a temperature difference between the object in question and its surroundings, there will be a net energy transfer in the form of heat; a colder object will be warmed at the expense of its surroundings, a warmer object cooled. And if the object in question is at the same temperature as its surrounding, the net radiation energy exchange will be zero.

In either case, the characteristic spectrum of the radiation depends on the object and its surroundings' absolute temperatures. The topic of this volume, radiation thermometry, or more generally, non-contact temperature measurement, involves taking advantage of this radiation dependence on temperature to measure the temperature of objects and masses without the need for direct contact.

Radiation Basics

The development of the mathematical relationships to describe radiation were a major step in the development of modern radiation thermometry theory. The ability to quantify radiant energy comes, appropriately enough, from Planck's quantum theory. Planck assumed that radiation was formed in discrete energy packages called photons, or quanta, the magnitude of which are dependent on the wavelength of the radiation. The total energy of a quantum, E, is found by multiplying Planck's constant, h = 6.6256×10^{-34}, and, the radiation frequency, υ, in cycles per second.

In 1905, Albert Einstein postulated that these quanta are particles moving at the speed of light, c = 2.9979×10^{8} m/s. If these photons traveled at the speed of light, then they must obey the theory of relativity, stating $E^2 = c^2p^2$, and each photon must have the momentum p = E/c = h/λ. The frequency can be found by dividing the speed of light by its particle wavelength $\upsilon = c/\lambda$. Substituting for momentum:

$$\mathbf{E = h\upsilon = hc/\lambda}$$

From this equation, it is apparent that the amount of energy emitted depends on the wavelength (or frequency). The shorter the wavelength, the higher the energy.

Emitted radiation consists of a continuous, non-uniform distribution of monochromatic (single-wavelength) components, varying widely with wavelength and direction. The amount of radiation per unit wavelength interval, referred to as the spectral concentration, also varies with wavelength. And the magnitude of radiation at any wavelength as well as the spectral distribution vary with the properties and temperature of the emitting surface. Radiation is also directional. A surface may prefer a particular direction to radiate energy. Both spectral and directional distribution must be considered in studying radiation.

Wavelength can be thought of as a type of address to find where a ray's energy is located. The map containing all the wavelengths of electromagnetic radiation is called the electromagnetic spectrum (see the inside front cover of this volume). The short wavelengths are the gamma rays, X-rays, and ultraviolet (UV) radiation,

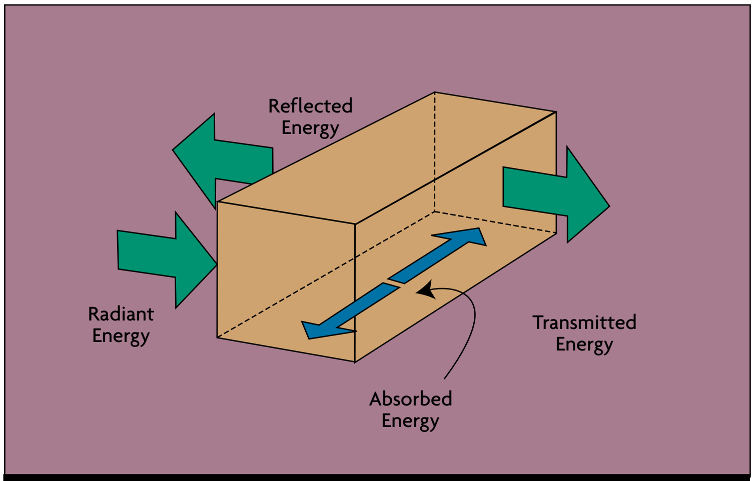

Figure 2-1: Radiation Energy Balance

containing the highest amount of energy emitted. The intermediate portion of the spectrum, the heat region, extends from approximately 0.1 to 1000 µm (micrometers or microns: 1,000,000 microns = 1 meter), and includes a portion of the ultraviolet and all of the visible (VIS) and infrared (IR) waves. This portion is termed thermal radiation, and is important in the study of heat transfer and radiation thermometry.

Non-contact temperature sensors work in the infrared portion of the spectrum. The infrared range falls between 0.78 microns and 1000 microns in wavelength, and is invisible to the naked eye. The infrared is region can be divided into three regions: near-infrared (0.78-3.0 microns); middle infrared (3-30 microns); and far infrared (30-300 microns). The range between 0.7 microns and 14 microns is normally used in infrared temperature measurement. The divisions have been related to the transmission of the atmosphere for different types of applications.

Blackbody Concepts

Incident energy striking an object from the surroundings, can be absorbed by the object, reflected by the object, or transmitted through the object (if it is not opaque) as seen in Figure 2-1. If the object is at a constant temperature, then the rate at which it emits energy must equal the rate at which it absorbs energy, otherwise the object would cool (emittance greater than absorption), or warm (emittance less than absorption). Therefore, for bodies at constant temperature, the emittance (absorption), the reflection and the transmittance of energy equals unity.

Central to radiation thermometry is the concept of the blackbody. In 1860, Kirchhoff defined a blackbody as a surface that neither reflects or transmits, but absorbs all incident radiation, independent of direction and wavelength. The fraction of radiation absorbed by a real body is called absorptivity, α. For an ideal blackbody, the absorptivity is 1.0 ($\alpha_b = 1$). For non-blackbodies, the absorption is a fraction of the radiation heat transfer incident on a surface, or $0 \leq \alpha \leq 1$. Hence, in term of radiation heat transfer, q":

$$q''_{absorbed} = \alpha q''_{incident}$$

In addition to absorbing all incident radiation, a blackbody is a perfect radiating body. To describe the emitting capabilities of a surface in comparison to a blackbody, Kirchoff defined emissivity (ε) of a real surface as the ratio of the thermal radiation emitted by a surface at a given temperature to that of a blackbody at the same temperature and for the same spectral and directional conditions.

This value also must be considered by a non-contact temperature sensor when taking a temperature measurement. The total emissivity for a real surface is the ratio of the total amount of radiation emitted by a surface in comparison to a blackbody at the same temperature. The tables beginning on p. 72 give representative emissivity values for a wide range of materials. If precise temperature measurements are required, however, the surface's actual emittivity value should be obtained. (Although often used interchangeably, the terms emissivity and emittivity have technically different meanings. Emissivity refers to a property of a material, such as cast iron, whereas emittivity refers to a property

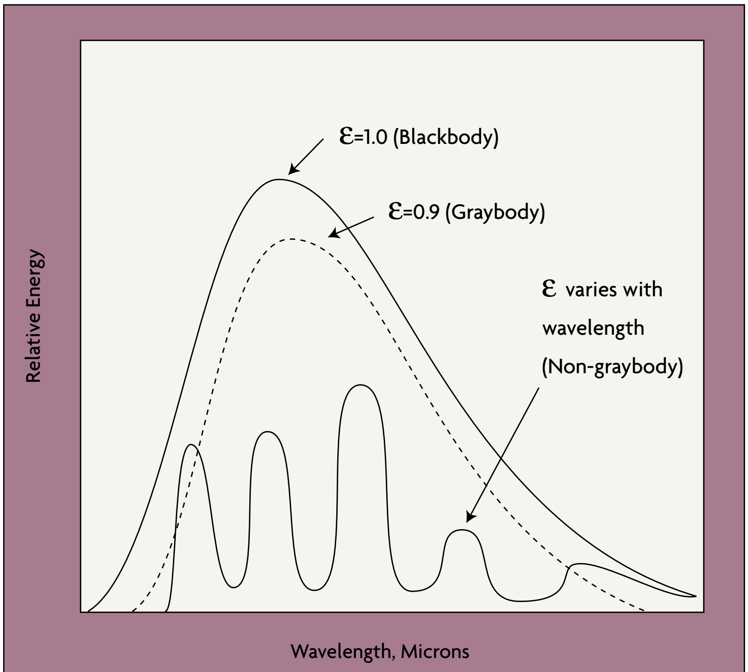

Figure 2-2: Spectral Distributions

of a specific surface.)

In 1879, Stefan concluded based on experimental results that the radiation emitted from the surface of an object was proportional to the fourth power of the absolute temperature of the surface. The underlying theory was later developed by Boltzmann, who showed that the radiation given off by a blackbody at absolute temperature T_s (K) is equal to:

$$q'' = \sigma T_s^4$$

where (is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m^2 • K^4). The heat transfer rate by radiation for a non-blackbody, per unit area is defined as:

$$q'' = \alpha\sigma(T_s^4 - T_{sur}^4)$$

where T_s is the surface temperature and T_{sur} is the temperature of the surroundings.

Although some surfaces come close to blackbody performance, all real objects and surfaces have emissivities less than 1. Non-blackbody objects are either graybodies, whose emissivity does vary with wavelength, or non-graybodies, whose emissivities vary with wavelength. Most organic objects are graybodies, with an emissivity between 0.90 and 0.95 (Figure 2-2).

The blackbody concept is important because it shows that radiant power depends on temperature. When using non-contact temperature sensors to measure the energy emitted from an object, depending on the nature of the surface, the emissivity must be taken into account and corrected. For example, an object with an emissivity of 0.6 is only radiating 60% of the energy of a blackbody. If it is not corrected for, the temperature will be lower than the actual temperature. For objects with an emissivity less than 0.9, the heat transfer rate of a real surface is identified as:

$$q'' = \varepsilon\sigma T_s^4$$

The closest approximation to a blackbody is a cavity with an interior surface at a uniform temperature T_s, which communicates with the surroundings by a small hole having a diameter small in comparison to the dimensions of the cavity (Figure 2-3). Most of the radiation entering the opening is either absorbed or reflected within the cavity (to ultimately be absorbed), while negligible radiation exits the aperture. The body approximates a perfect absorber, independent of the cavity's surface properties.

The radiation trapped within the interior of the cavity is absorbed and reflected so that the radiation within the cavity is equally distributed—some radiation is absorbed and some reflected. The incident radiant energy falling per unit time on any surface per unit area within the cavity is defined as the irradiance G_λ (W/m^2 • µm). If the total irradiation G (W/m^2) represents the rate at which radiation is incident per unit area from all directions and at all wavelengths, it follows that:

$$G = \int_{0\rightarrow\infty} G_\lambda \, (d\lambda)$$

If another blackbody is brought into the cavity with an identical temperature as the interior walls of the cavity, the blackbody will maintain its current temperature. Therefore, the rate at which the energy absorbed by the inner surface of the cavity will equal the rate at which it is emitted.

In many industrial applications, transmission of radiation, such as through a layer of water or a glass plate, must be considered. For a spectral component of the irradiation, portions may be reflected, absorbed, and transmitted. It follows that:

$$G_\lambda = G_{\lambda,ref} + G_{\lambda,abs} + G_{\lambda,tran}$$

In many engineering applications, however, the medium is opaque to the incident radiation. Therefore, $G_{\lambda,tran} = 0$, and the remaining absorption and reflection can be treated as surface phenomenon. In other words, they are controlled by processes occurring within a fraction of a micrometer from the irradiated surface. It is therefore appropriate to say that the irradiation is absorbed and reflected by the surface, with the relative magnitudes of $G_{\lambda,ref}$ and $G_{\lambda,abs}$ depending on the wavelength and the nature of the surface.

Radiation transfer by a non-blackbody encompasses a wide range of wavelengths and directions. The spectral hemispherical emissive power, E_λ (W/m^2 • µm) is defined as the rate at which radiation is emitted per unit area at all possible wavelengths and in all possible directions from a surface, per unit wavelength dλ about λ and per unit surface area.

Although the directional distribution of surface emission varies depends on the surface itself, many surfaces approximate diffuse emitters. That is, the intensity of emitted radiation is independent of the direction in which the energy is incident or emitted. In this case, the total, hemispherical (spectral) emissive power, E_λ (W/m^2) is defined as:

$$E_\lambda(\lambda) = \pi I_{\lambda,e}(\lambda)$$

or

$$E = \pi I_e$$

where I_e is the total intensity of the emitted radiation, or the rate at which radiant energy is emitted at a specific wavelength, per unit area of the emitting surface normal to the direction, per unit solid angle about this direction, and per unit wavelength. Notice that E_λ is a flux based on the actual surface area, where $I_{\lambda e}$ is based on the projected area. In approximating a blackbody, the radiation is almost entirely absorbed by the cavity. Any radiation that exits the cavity is due to the surface temperature only.

The spectral characteristics of blackbody radiation as a function of temperature and wavelength were determined by Wilhelm Wien in 1896. Wien derived his law for the distribution of energy in the emission spectrum as:

$$E_{\lambda,b}(\lambda,T) = 2h^2/\lambda^5 [\exp(hc_o/\lambda kT)]$$

where $E_{\lambda,b}$ (b for blackbody) represents the intensity of radiation emitted by a blackbody at temperature T, and wavelength λ per unit wavelength interval, per unit time, per unit solid angle, per unit area. Also, $h = 6.626 \times 10^{-24}$ J•s and $k = 1.3807 \times 10^{-23}$ $J \cdot K^{-1}$ are the universal Planck and Boltzman constants, respectively; $c_o = 2.9979 \times 10^8$ m/s is the speed of light in a vacuum, and T is the absolute temperature of the blackbody in Kelvins (K).

Due to the fact that deviations appeared between experimental results and the equation, Planck suggested in 1900 a refinement that better fit reality:

$$E_{\lambda,b}(\lambda,T) = 2h^2/\lambda^5 [\exp(hc_o/\lambda kT) - 1]$$

It is from this equation that Planck postulated his quantum theory. A more convenient expression for this equation, referred to as the Planck distribution law (Figure 2-4), is:

$$E_{\lambda,b}(\lambda,T) = \pi I_{\lambda,b}(\lambda,T) = C_1/\lambda^5[\exp(C_2/\lambda T) - 1]$$

where the first and second radiation constants are $C_1 = 2\pi h c_o^2 = 3.742 \times 10^8$ W • $\mu m^4/m^2$ and $C_2 = (hc_o/k) = 1.439 \times 10^4$ µm • K.

Planck's distribution shows that as wavelength varies, emitted radiation varies continuously. As temperature increases, the total amount of energy emitted increases and the peak of the curve shifts to the left, or toward the shorter wavelengths. In considering the electromagnetic spectrum, it is apparent that bodies with very high temperatures emit energy in the visible spectrum as wavelength decreases. Figure 2-4 also shows that there is more energy difference per degree at shorter wavelengths.

From Figure 2-4, the blackbody spectral distribution has a maximum wavelength value, λ_{max}, which depends on the temperature. By differentiating equation 2.12 with respect to λ and setting the result equal to zero:

$$\lambda_{max} T = C_3$$

where the third radiation constant, $C_3 = 2897.7$ µm • K. This is known as Wien's displacement law. The dashed line in Figure 2-4 defines this equation and locates the maximum radiation values for each temperature, at a specific wavelength. Notice that maximum radiance is associated with higher temperatures and lower wavelengths.

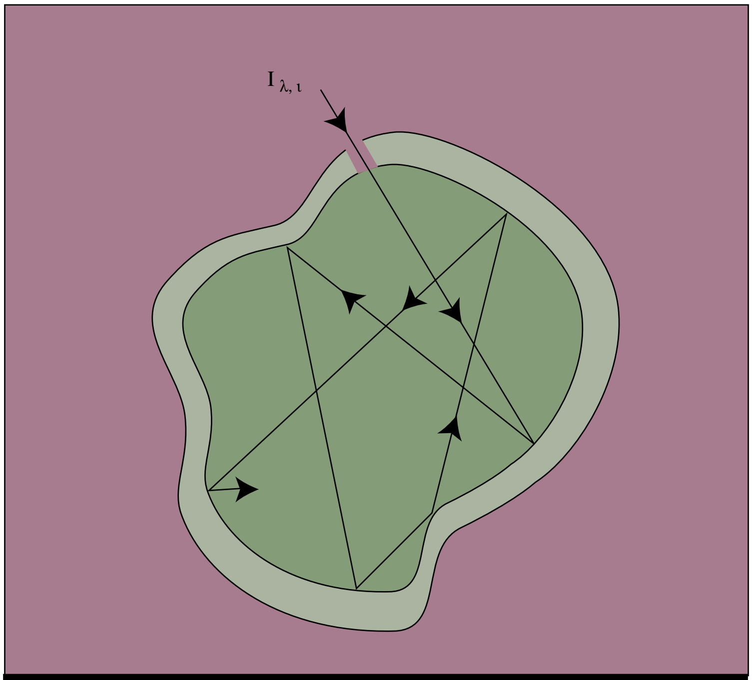

Figure 2-3: An Isothermal Blackbody Cavity

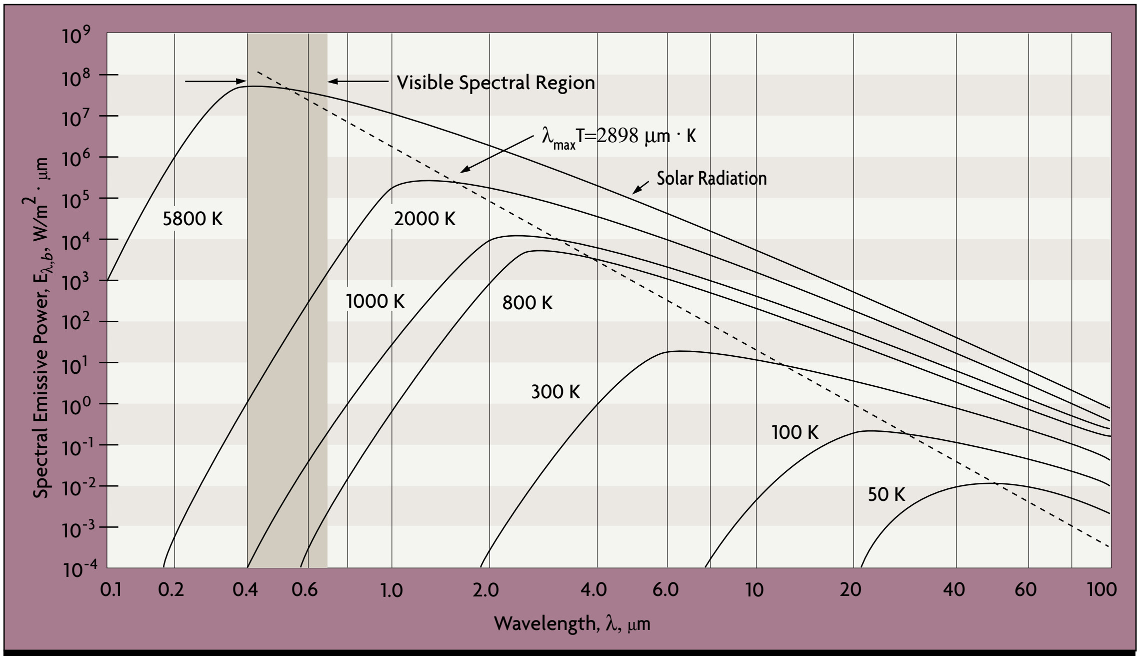

Figure 2-4: Planck Prediction of Blackbody Emissive Power

From Blackbodies to Real Surfaces

At first it would seem that a radiation thermometer would utilize the entire spectrum, capturing most of the radiant emission of a target in its particular temperature range. There are several reasons why this is not practical.

In the equations for infrared radiation derived above, it was found that at very low wavelengths, the radiance increases rapidly with temperature, in comparison to the increase at higher wavelengths, as shown in Figure 2-4. Therefore, the rate of radiance change is always greater at shorter wavelengths. This could mean more precise temperature measurement and tighter temperature control. However, at a given short wavelength there is a lower limit to the temperature that can be measured. As the process temperature decreases, the spectral range for an infrared thermometer shifts to longer wavelengths and becomes less accurate.

The properties of the material at various temperatures must also be considered. Because no material emits as efficiently as a blackbody at a given temperature, when measuring the temperature of a real target, other considerations must be made. Changes in process material emissivity, radiation from other sources, and losses in radiation due to dirt, dust, smoke, or atmospheric absorption can introduce errors.

The absorptivity of a material is the fraction of the irradiation absorbed by a surface. Like emission, it can be characterized by both a directional and spectral distribution. It is implicit that surfaces may exhibit selective absorption with respect to wavelength and direction of the incident radiation. However, for most engineering applications, it is desirable to work with surface properties that represent directional averages. The spectral, hemispherical absorptivity for a real surface $\alpha_\lambda(\lambda)$is defined as:

$$\alpha_\lambda(\lambda) \cong G_{\lambda,abs}(\lambda)/G_\lambda(\lambda)$$

where $G_{\lambda,abs}$ is the portion of irradiation absorbed by the surface. Hence, α_λ depends on the directional distribution of the incident radiation, as well as on the wavelength of the radiation and the nature of the absorbing surface. The total, hemispherical absorptivity, α, represents an integrated average over both directional and wavelength. It is defined as the fraction of the total irradiation absorbed by a surface, or:

$$\alpha \cong G_{abs}/G$$

The value of α depends on the spectral distribution of the incident radiation, as well as on its directional distribution and the nature of the absorbing surface. Although

α is independent on the temperature of the surface, the same may not be said for the total, hemispherical emissivity. Emissivity is strongly temperature dependent.

The reflectivity of a surface defines the fraction of incident radiation reflected by a surface. Its specific definition may take several different forms. We will assume a reflectivity that represents an integrated average over the hemisphere associated with the reflected radiation to avoid the problems from the directional distribution of this radiation. The spectral, hemispherical reflectivity $\rho_\lambda(\lambda)$, then, is defined as the spectral irradiation that is reflected by the surface. Therefore:

$$\rho_\lambda(\lambda) \cong G_{\lambda,ref}(\lambda)/G_\lambda(\lambda)$$

where $G_{\lambda,ref}$ is the portion of irradiation reflected by the surface. The total, hemispherical reflectivity ρ is then defined as:

$$\rho \cong G_{ref}/G$$

If the intensity of the reflected radiation is independent of the direction of the incident radiation and the direction of the reflected radiation, the surface is said to be diffuse emitter. In contrast, if the incident angle is equivalent to the reflected angle, the surface is a specular reflector. Although no surface is perfectly diffuse or specular, specular behavior can be approximated by polished or mirror-like surfaces. Diffuse behavior is closely approximated by rough surfaces and is likely to be encountered in industrial applications.

Transmissivity is the amount of radiation transmitted through a surface. Again, assume a transmissivity that represents an integrated average. Although difficult to obtain a result for transparent media, hemispherical transmissivity is defined as:

$$\tau_\lambda = G_{\lambda,tr}(\lambda)/G_\lambda(\lambda)$$

where $G_{\lambda,tr}$ is the portion of irradiation reflected by the surface. The total hemispherical transmissivity is:

$$\tau = G_{tr}/G$$

The sum of the total fractions of energy absorbed (α), reflected (ρ), and transmitted (τ) must equal the total amount of radiation incident on the surface. Therefore, for any wavelength:

$$\rho_\lambda + \tau_\lambda + \alpha_\lambda = 1$$

This equation applies to a semitransparent medium. For properties that are averaged over the entire spectrum, it follows that:

$$\rho + \tau + \alpha = 1$$

For a medium that is opaque, the value of transmission is equal to zero. Absorption and reflection are surface properties for which:

$$\rho_\lambda + \alpha_\lambda = 1$$

and

$$\rho + \alpha = 1$$

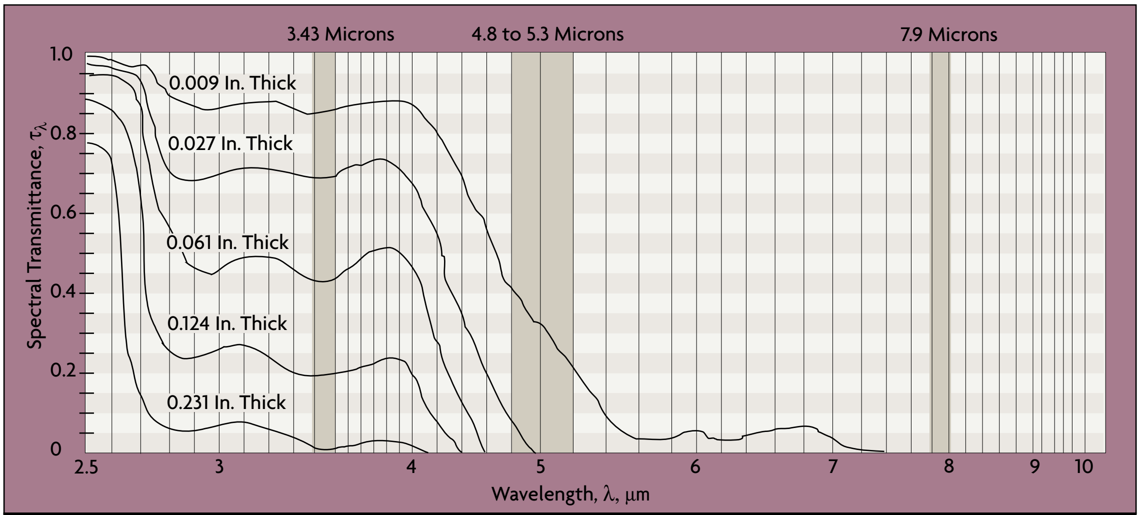

Figure 2-5: Soda-Lime Glass Spectral Transmittance

For a blackbody, the transmitted and reflected fractions are zero and the emissivity is unity.

An example of a material whose emissivity characteristics change radically with wavelength is glass. Soda-lime glass is an example of a material which drastically changes its emissivity characteristics with wavelength (Figure 2-5). At wavelengths below about 2.6 microns, the glass is highly transparent and the emissivity is nearly zero. Beyond 2.6 microns, the glass becomes increasingly more opaque. Beyond 4 microns, the glass is completely opaque and the emissivity is above 0.97. T

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IR Thermometers & Pyrometers

Pyrometer is derived from the Greek root pyro, meaning fire. The term pyrometer was originally used to denote a device capable of measuring temperatures of objects above incandescence, objects bright to the human eye. The original pyrometers were non-contacting optical devices which intercepted and evaluated the visible radiation emitted by glowing objects. A modern and more correct definition would be any non-contacting device intercepting and measuring thermal radiation emitted from an object to determine surface temperature. Thermometer, also from a Greek root thermos, signifying hot, is used to describe a wide assortment of devices used to measure temperature. Thus a pyrometer is a type of thermometer. The designation radiation thermometer has evolved over the past decade as an alternative to pyrometer. Therefore the terms pyrometer and radiation thermometer are used interchangeably by many references.

A radiation thermometer, in very simple terms, consists of an optical system and detector. The optical system focuses the energy emitted by an object onto the detector, which is sensitive to the radiation. The output of the detector is proportional to the amount of energy radiated by the target object (less the amount absorbed by the optical system), and the response of the detector to the specific radiation wavelengths. This output can be used to infer the objects temperature. The emittivity, or emittance, of the object is an important variable in converting the detector output into an accurate temperature signal.

Infrared radiation thermometers/pyrometers, by specifically measuring the energy being radiated from an object in the 0.7 to 20 micron wavelength range, are a subset of radiation thermometers. These devices can measure this radiation from a distance. There is no need for direct contact between the radiation thermometer and the object, as there is with thermocouples and resistance temperature detectors (RTDs). Radiation thermometers are suited especially to the measurement of moving objects or any surfaces that can not be reached or can not be touched.

But the benefits of radiation thermometry have a price. Even the simplest of devices is more expensive than a standard thermocouple or resistance temperature detector (RTD) assembly, and installation cost can exceed that of a standard thermowell. The devices are rugged, but do require routine maintenance to keep the sighting path clear, and to keep the optical elements clean. Radiation thermometers used for more difficult applications may have more complicated optics, possibly rotating or moving parts, and microprocessor-based electronics. There are no industry accepted calibration curves for radiation thermometers, as there are for thermocouples and RTDs. In addition, the user may need to seriously investigate the application, to select the optimum technology, method of installation, and compensation needed for the measured signal, to achieve the performance desired.

Emittance, Emissivity, and the N Factor

In an earlier chapter, emittance was identified as a critical parameter in accurately converting the output of the detector used in a radiation thermometer into a value representing object temperature.

The terms emittance and emissivity are often used interchangeably.

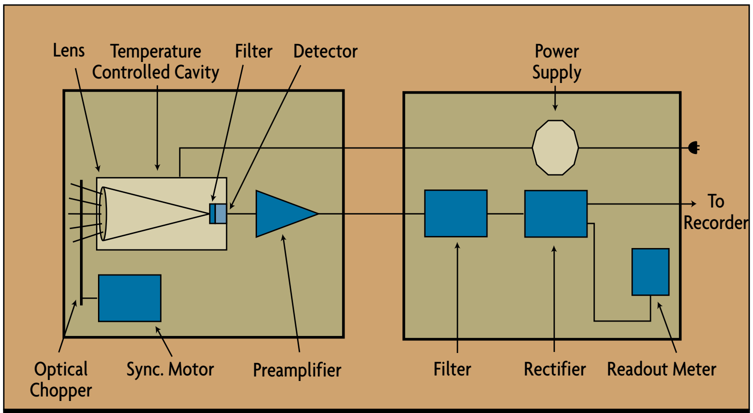

Figure 3-1: Traditional Infrared Thermometer

There is, however, a technical distinction. Emissivity refers to the properties of a material; emittance to the properties of a particular object. In this latter sense, emissivity is only one component in determining emittance. Other factors, including shape of the object, oxidation and surface finish must be taken into account.

The apparent emittance of a material also depends on the temperature at which it is determined, and the wavelength at which the measurement is taken. Surface condition affects the value of an object's emittance, with lower values for polished surfaces, and higher values for rough or matte surfaces. In addition, as materials oxidize, emittance tends to increase, and the surface condition dependence decreases. Representative emissivity values for a range of common metals and nonmetals at various temperatures are given in the tables starting on p. 72.

The basic equation used to describe the output of a radiation thermometer is:

$$V(T) = \varepsilon K T^N$$

Where:

- ε = *emittivity*
- V(T) = *thermometer output with temperature*
- K = *constant*
- T = *object temperature*
- N = *N factor (= 14388/(λT))*
- λ = *equivalent wavelength*

A radiation thermometer with the highest value of N (shortest possible equivalent wavelength) should be selected to obtain the least dependence on target emittance changes. The benefits of a device with a high value of N extends to any parameter that effects the output V. A dirty optical system, or absorption of energy by gases in the sighting path, has less effect on an indicated temperature if N has a high value.

The values for the emissivities of readings is due to the emissivity, which is, of course, less than one. For temperatures up to 500°F (260°C) emissivity values can be determined experimentally by putting a piece of black masking tape on the target sur-

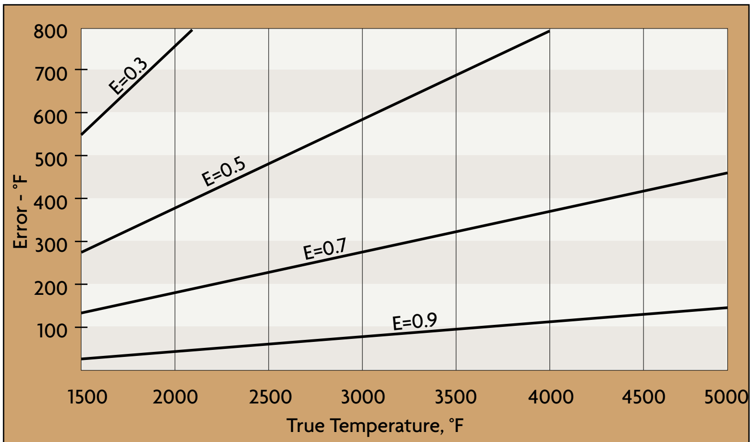

Figure 3-2: Effect of Non-Blackbody Emissivity on IR Thermometer Error

almost all substances are known and published in reference literature. However, the emissivity determined under laboratory conditions seldom agrees with actual emittance of an object under real operating conditions. For this reason, one is likely to use published emissivity data when the values are high. As a rule of thumb, most opaque non-metallic materials have a high and stable emissivity (0.85 to 0.90). Most unoxidized, metallic materials have a low to medium emissivity value (0.2 to 0.5). Gold, silver and aluminum are exceptions, with emissivity values in the 0.02 to 0.04 range. The temperature of these metals is very difficult to measure with a radiation thermometer.

One way to determine emissivity experimentally is by comparing the radiation thermometer measurement of a target with the simultaneous measurement obtained using a thermocouple or RTD. The difference in readings is due to the emissivity, which is, of course, less than one. For temperatures up to 500°F (260°C) emissivity values can be determined experimentally by putting a piece of black masking tape on the target surface. Using a radiation pyrometer set for an emissivity of 0.95, measure the temperature of the tape surface (allowing time for it to gain thermal equilibrium). Then measure the temperature of the target surface without the tape. The difference in readings determines the actual value for the target emissivity.

Many instruments now have calibrated emissivity adjustments. The adjustment may be set to a value of emissivity determined from tables, such as those starting on p. 72, or experimentally, as described in the preceding paragraph. For highest accuracy, independent determination of emissivity in a lab at the wavelength at which the thermometer measures, and possibly at the expected temperature of the target, may be necessary.

Emissivity values in tables have been determined by a pyrometer sighted perpendicular to the target.

If the actual sighting angle is more than 30 or 40 degrees from the normal to the target, lab measurement of emissivity may be required.

In addition, if the radiation pyrometer sights through a window, emissivity correction must be provided for energy lost by reflection from the two surfaces of the window, as well as absorption in the window. For example, about 4% of radiation is reflected from glass surfaces in the infrared ranges, so the effective transmittance is 0.92. The loss through other materials can be determined from the index of refraction of the material at the wavelength of measurement.

The uncertainties concerning emittance can be reduced using short wavelength or ratio radiation thermometers. Short wavelengths, around 0.7 microns, are useful because the signal gain is high in this region. The higher response output at short wavelengths tends to swamp the effects of emittance variations. The high gain of the radiated energy also tends to swamp the absorption effects of steam, dust or water vapor in the sight path to the target. For example, setting the wavelength at such a band will cause the sensor to read within ±5 to ±10 degrees of absolute temperature when the material has an emissivity of 0.9 (±0.05). This represents about 1% to 2% accuracy.

Types of Radiation Thermometers

Historically, as shown in Figure 3-1, a radiation thermometer consisted of an optical system to collect the energy emitted by the target; a detector to convert this energy to an electrical signal; an emittivity adjustment to match the thermometer calibration to the specific emitting characteristics of the target, and an ambient temperature compensation circuit, to ensure that temperature variations inside the thermometer due to ambient conditions did not affect accuracy.

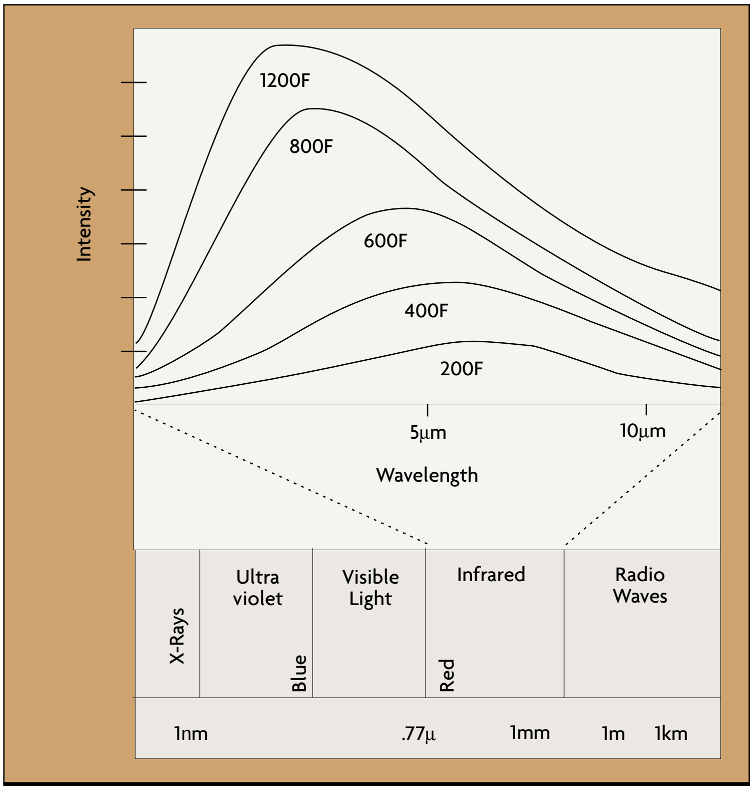

Figure 3-3: Blackbody Radiation in the Infrared

The modern radiation thermometer is still based on this concept. However the technology has become more sophisticated to widen the scope of the applications that can be handled. For example, the number of available detectors has greatly increased, and, thanks to selective filtering capabilities, these detectors can more efficiently be matched to specific applications, improving measurement performance. Microprocessor-based electronics can use complex algorithms to provide real time linearization and compensation of the detector output for higher precision of measured target temperature. Microprocessors can display instantaneous measurements of several variables (such as current temperature, minimum temperature measured, maximum temperature measured, average temperature or temperature differences) on integral LCD display screens.

A convenient classification of radiation thermometers is as follows:

- Broadband radiation thermometers/pyrometers;
- Narrow band radiation thermometers/pyrometers;
- Ratio radiation thermometers/pyrometers;
- Optical pyrometers; and
- Fiber optic radiation thermometers/pyrometers.

These classifications are not rigid. For example, optical pyrometers can be considered a subset of narrow band devices. Fiber optic radiation thermometers, to be discussed in detail in another section, can be classified as wide band, narrow band, or ratio devices. Likewise, infrared radiation thermometers can be considered subsets of several of these classes.

Broadband Radiation

Broadband radiation thermometers typically are the simplest devices, cost the least, and can have a response from 0.3 microns wavelength to an upper limit of 2.5 to 20 microns. The low and high cut-offs of the broadband thermometer are a function of the specific optical system being used. They are termed broadband because they measure a significant fraction of the thermal radiation emitted by the object, in the temperature ranges of normal use.

Broadband thermometers are dependent on the total emittance of the surface being measured. Figure 3-2 shows the error in reading for various emissivities and temperatures when a broadband device is calibrated for a blackbody. An emissivity control allows the user to compensate for these errors, so long as the emittance does not change.

The path to the target must be unobstructed. Water vapor, dust, smoke, steam and radiation absorptive gases present in the atmosphere can attenuate emitted radiation from the target and cause the thermometer to read low.

The optical system must be kept clean, and the sighting window protected against any corrosives in the environment.

Standard ranges include 32 to 1832°F (0 to 1000°C), and 932 to 1652°F (500 to 900°C). Typical accuracy is 0.5 to 1% full scale.

Narrow Band Radiation

As the name indicates, narrow band radiation thermometers operate over a narrow range of wavelengths. Narrow band devices can also be referred to as single color thermometers/pyrometers (see Optical Pyrometers). The specific detector used determines the spectral response of the particular device. For example, a thermometer using a silicon cell detector will have a response that peaks at approximately 0.9 microns, with the upper limit of usefulness being about 1.1 microns. Such a device is useful for measuring temperatures above 1102°F (600°C). Narrow band thermometers routinely have a spectral response of less than 1 micron.

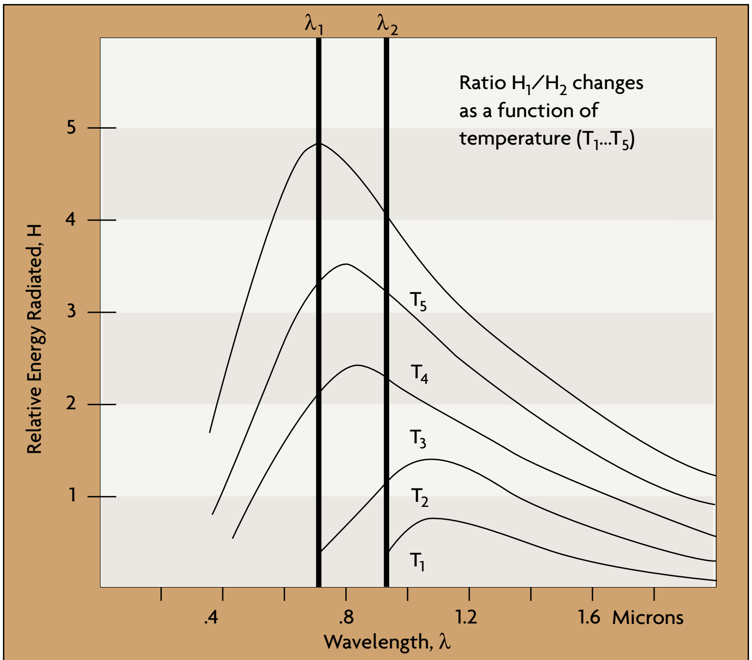

Figure 3-4: The 'Two-Color' IR Thermometer

Narrow band thermometers use filters to restrict response to a selected wavelength. Probably the most important advance in radiation thermometry has been the introduction of selective filtering of the incoming radiation, which allows an instrument to be matched to a particular application to achieve higher measurement accuracy. This was made possible by the availability of more sensitive detectors and advances in signal amplifiers.

Common examples of selective spectral responses are 8 to 14 microns, which avoids interference from atmospheric moisture over long paths; 7.9 microns, used for the measurement of some thin film plastics; 5 microns, used for the measurement of glass surfaces; and 3.86 microns, which avoids interference from carbon dioxide and water vapor in flames and combustion gases.

The choice of shorter or longer wavelength response is also dictated by the temperature range. The peaks of radiation intensity curves move towards shorter wavelengths as temperature increases, as shown in Figure 3-3. Applications that don't involve such considerations may still benefit from a narrow spectral response around 0.7 microns. While emissivity doesn't vary as much as you decrease the wavelength, the thermometer will lose sensitivity because of the reduced energy available.

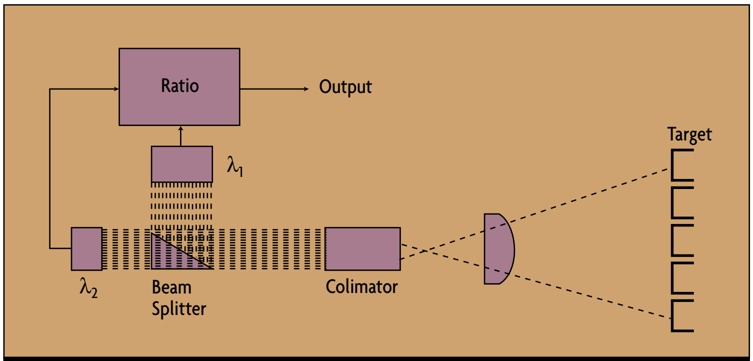

Figure 3-5: Beam-Splitting in the Ratio IR Thermometer

Narrow band thermometers with short wavelengths are used to measure high temperatures, greater than 932°F (500°C), because radiation energy content increases as wavelengths get shorter. Long wavelengths are used for low temperatures -50°F (-45.5°C).

Narrow band thermometers range from simple hand-held devices, to sophisticated portables with simultaneous viewing of target and temperature, memory and printout capability, to on-line, fixed mounted sensors with remote electronics having PID control.

Standard temperature ranges vary from one manufacturer to the next, but some examples include: -36 to 1112°F (-37.78 to 600°C), 32 to 1832°F (0 to 1000°C), 1112 to 5432°F (600 to 3000°C) and 932 to 3632°F (500 to 2000°C). Typical accuracy is 0.25% to 2% of full scale.

Ratio Radiation

Also called two-color radiation thermometers, these devices measure the radiated energy of an object between two narrow wavelength bands, and calculates the ratio of the two energies, which is a function of the temperature of the object. Originally, these were called two color pyrometers, because the two wavelengths corresponded to different colors in the visible spectrum (for example, red and green). Many people still use the term two-color pyrometers today, broadening the term to include wavelengths in the infrared. The temperature measurement is dependent only on the ratio of the two energies measured, and not their absolute values as shown in Figure 3-4. Any parameter, such as target size, which affects the amount of energy in each band by an equal percentage, has no effect on the temperature indication. This makes a ratio thermometer inherently more accurate. (However, some accuracy is lost when you're measuring small differences in large signals). The ratio technique may eliminate, or reduce, errors in temperature measurement caused by changes in emissivity, surface finish, and energy absorbing materials, such as water vapor, between the thermometer and the target. These dynamic changes must be seen identically by the detector at the two wavelengths being used.

Emissivity of all materials does not change equally at different wavelengths. Materials for which emissivity does change equally at different wavelengths are called gray bodies. Materials for which this is not true are called non-gray bodies. In addition, not all forms of sight path obstruction attenuate the ratio wavelengths equally. For example, if there are particles in the sight path that have the same size as one

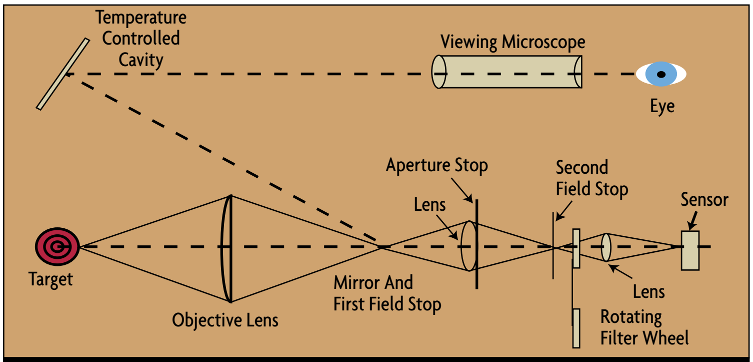

Figure 3-6: Ratio Pyrometry Via a Filter Wheel

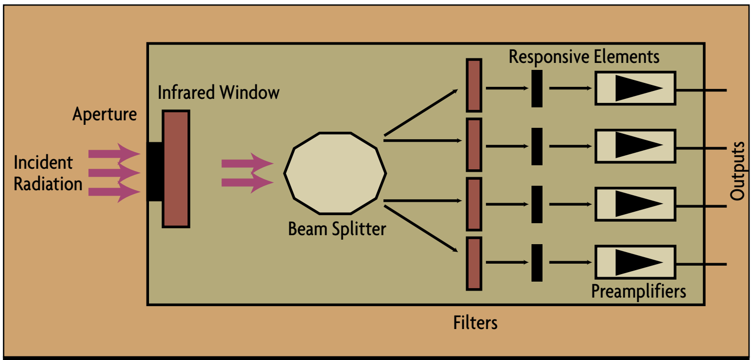

Figure 3-7: Schematic of a Multispectral IR Thermometer

of the wavelengths, the ratio can become unbalanced.

Phenomena which are non-dynamic in nature, such as the non-gray bodiness of materials, can be dealt with by biasing the ratio of the wavelengths accordingly. This adjustment is called slope. The appropriate slope setting must be determined experimentally.

Figure 3-5 shows a schematic diagram of a simple ratio radiation thermometer. Figure 3-6 shows a ratio thermometer where the wavelengths are alternately selected by a rotating filter wheel.

Some ratio thermometers use more than two wavelengths. A multi-wavelength device is schematically represented in Figure 3-7. These devices employ a detailed analysis of the target's surface characteristics regarding emissivity with regard to wavelength, temperature, and surface chemistry. With such data, a computer can use complex algorithms to relate and compensate for emissivity changes at various conditions. The system described in Figure 3-7 makes parallel measurement possible in four spectral channels in the range from 1 to 25 microns. The detector in this device consists of an optical system with a beam splitter, and interference filters for the spectral dispersion of the incident radiation. This uncooled thermometer was developed for gas analysis. Another experimental system, using seven different wavelengths demonstrated a resolution of ±1°C measuring a blackbody source in the range from 600 to 900°C. The same system demonstrated a resolution of ±4° C measuring an object with varying emittance over the temperature range from 500 to 950°C.

Two color or multi-wavelength thermometers should be seriously considered for applications where accuracy, and not just repeatability, is critical, or if the target object is undergoing a physical or chemical change.

Ratio thermometers cover wide temperature ranges. Typical commercially available ranges are 1652 to 5432° F (900 to 3000°C) and 120 to 6692°F (50 to 3700°C). Typical accuracy is 0.5% of reading on narrow spans, to 2% of full scale.

Optical Pyrometers

Optical pyrometers measure the radiation from the target in a narrow band of wavelengths of the thermal spectrum. The oldest devices use the principle of optical brightness in the visible red spectrum around 0.65 microns. These instruments are also called single color pyrometers. Optical pyrometers are now available for measuring energy wavelengths that extend into the infrared region. The term single color pyrometers has been broadened by some authors to include narrow band radiation thermometers as well.

Some optical designs are manually operated as shown in Figure 3-8.

Typical configuration of an industrial infrared temperature probe.

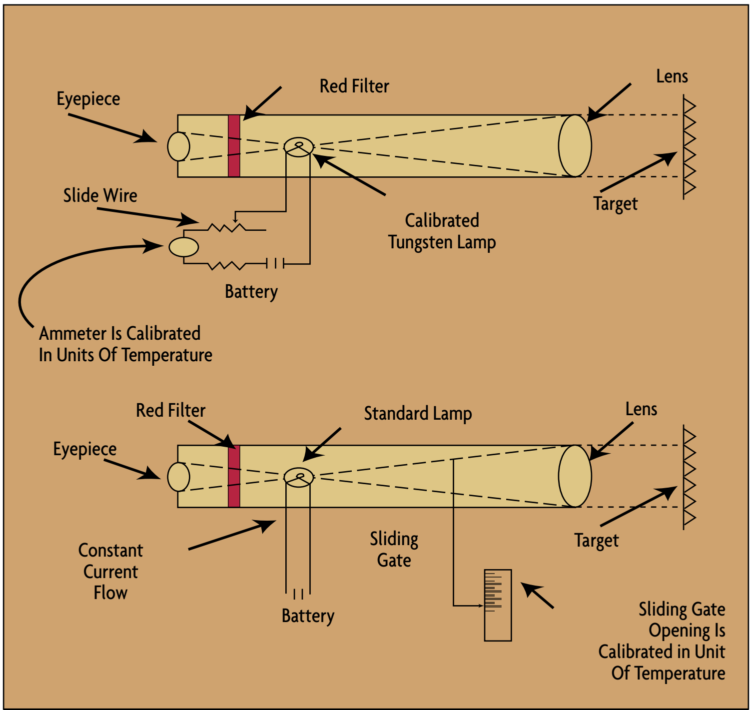

Figure 3-8: Optical Pyrometry By Visual Comparison

The operator sights the pyrometer on target. At the same time he/she can see the image of an internal lamp filament in the eyepiece. In one design, the operator adjusts the power to the filament, changing its color, until it matches the color of the target. The temperature of the target is measured based upon power being used by the internal filament. Another design maintains a constant current to the filament and changes the brightness of the target by means of a rotatable energy-absorbing optical wedge. The object temperature is related to the amount of energy absorbed by the wedge, which is a function of its annular position.

Automatic optical pyrometers, sensitized to measure in the infrared region, also are available. These instruments use an electrical radiation detector, rather than the human eye. This device operates by comparing the amount of radiation emitted by the target with that emitted by an internally controlled reference source. The instrument output is proportional to the difference in radiation between the target and the reference. A chopper, driven by a motor, is used to alternately expose the detector to incoming radiation and reference radiation. In some models, the human eye is used to adjust the focus. Figure 3-9 is a schematic of an automatic optical pyrometer with a dichroic mirror. Radiant energy passes through the lens into the mirror, which reflects infrared radiation to the detector, but allows visible light to pass through to an adjustable eyepiece. The calibrate flap is solenoid-operated from the amplifier, and when actuated, cuts off the radiation coming through the lens, and focuses the calibrate lamp on to the detector. The instrument may have a wide or narrow field of view. All the components can be packaged into a gun-shaped, hand-held instrument. Activating the trigger energizes the reference standard and read-out indicator.

Optical pyrometers have typical accuracy in the 1% to 2% of full scale range.

Fiber Optic Radiation

Although not strictly a class unto themselves, these devices use a light guide, such as a flexible transparent fiber, to direct radiation to the detector, and are covered in more detail in the chapter beginning on p. 43. The spectral response of these fibers extends to about 2 microns, and can be useful in measuring object temperatures to as low as 210°F (100°C). Obviously, these devices are particularly useful when it is difficult or impossible to obtain a clear sighting path to the target, as in a pressure chamber.

Design and Construction

The manufacturer of the radiation thermometer selects the detector and optical elements to yield the optimum compromise based upon the conflicting parameters of cost, accuracy, speed of response, and usable temperature range. The user should be cognizant of how the different detectors and optical elements affect the range of wavelengths over which a thermometer responds. The spectral response of a pyrometer will determine whether a usable measurement is possible, given the presence of atmospheric absorption, or reflections from other objects, or trying to measure the temperature of materials like glass or plastics.

Detectors

Thermal, photon, and pyroelectric detectors are typically used in radiation pyrometers. Radiation detectors are strongly affected by ambient temperature changes. High accuracy requires compensation for this ambient drift.

The responsivity of a radiation detector may be specified in terms of either the intensity of radiation, or the total radiant power incident upon the detector.

When the image formed by the target surface area is larger than the exposed area of the detector, the entire detector surface is subjected to a radiation intensity proportional to the brightness of the target. The total radiant power absorbed by the detector then depends on the area of its sensitive surface. The actual size of the effective target area is determined by the magnification of the optical system. Sensitivity typically is not uniform over the surface of a detector, but this has no effect if the target brightness is uniform. If substantial temperature differences occur on the target surface within the patch imaged on the detector, an ambiguously weighted average will result.

In the case of total radiant power, the area of the target surface imaged on the detector is limited by a stop optically conjugate to the detector. This area can be made arbitrarily small. As a result, local temperatures can be measured on the target body surface. The responsivity of the detector may depend on the location of this target source image on the detector surface. Constancy of calibration will depend on maintaining the element in a fixed position with respect to the optical system.

Thermal detectors are the most commonly used radiation thermometer detectors. Thermal detectors generate an output because they are heated by the energy they absorb. These detectors have lower sensitivity compared to other detector types, and their outputs are less affected by changes in the radiated wavelengths. The speed of response of thermal detectors is limited by their mass.

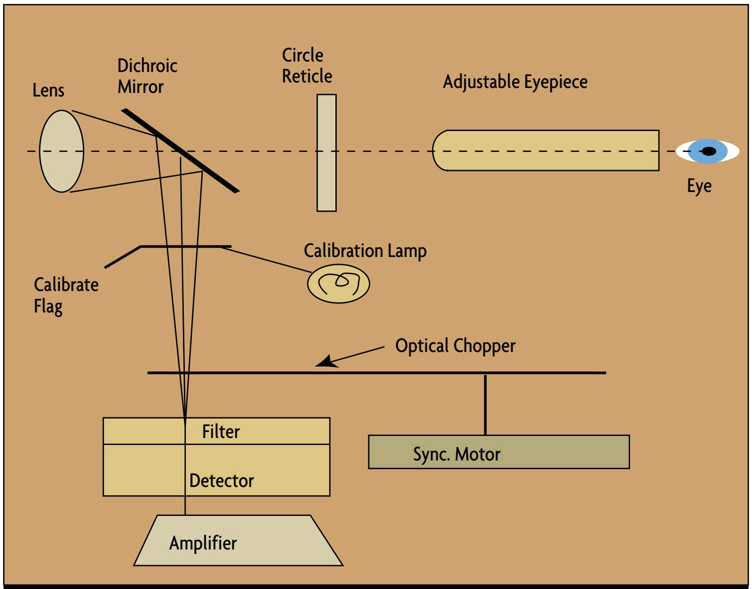

Figure 3-9: An Automatic Optical Pyrometer

Thermal detectors are blackened so that they will respond to radiation over a wide spectrum (broadband detectors). They are relatively slow, because they must reach thermal equilibrium whenever the target temperature changes. They can have time constants of a second or more, although deposited detectors respond much faster.

A thermopile consists of one or more thermocouples in series, usually arranged in a radial pattern so the hot junctions form a small circle, and the cold junctions are maintained at the local ambient temperature. Advanced thin film thermopiles achieve response times in the 10 to 15 millisecond range. Thermopiles also increase the output signal strength and are the best choice for broadband thermometers. Ambient temperature compensation is required when thermopile detectors are used. A thermostatically controlled thermometer housing is used to avoid ambient temperature fluctuations for low temperature work. Self-powered infrared thermocouples are covered in the chapter beginning on p. 38.

Bolometers are essentially resistance thermometers arranged for response to radiation. A sensing element with a thermistor, metal film, or metal wire transducer is often called a bolometer.

Photon detectors release electric charges in response to incident radiation. In lead sulfide and lead selenide detectors, the release of charge is measured as a change in resistance. In silicon, germanium, and indium antimonide, the release of charge is measured as a voltage output. Photon detectors have a maximum wavelength beyond which they will not respond. The peak response is usually at a wavelength a little shorter than the cutoff wavelength. Many radiation thermometers use photon detectors rather than thermal detectors, even though they measure over a narrower band of wavelength. This is because within the range of useful wavelengths, the photon detectors have a sensitivity 1000 to 100,000 times that of the thermal detector. Response time of these detectors is in microseconds. They are instable at longer wavelengths and higher temperatures. They are often used in narrow band thermometers, or broadband thermometers at medium temperatures (200 to 800°F/93 to 427°C), and often provided with cooling.

Pyroelectric detectors change surface charge in response to received radiation. The detector need not reach thermal equilibrium when the target temperature changes, since it responds to changes in incoming radiation. The incoming radiation must be chopped, and the detector output cannot be used directly. A chopper is a rotating or oscillating shutter employed to provide AC rather than DC output from the sensor. Relatively weak AC signals are more conveniently handled by conditioning circuitry. The detector change can be likened to a change in charge of a capacitor, which must be read with a high impedance circuit. Pyroelectric detectors have radiation absorbent coatings so they can be broadband detectors. Response can be restricted by selecting the coating material with appropriate characteristics.

Photon and pyroelectric detectors have thermal drift that can be overcome by temperature compensation (thermistor) circuitry, temperature regulation, auto null circuitry, chopping, and isothermal protection.

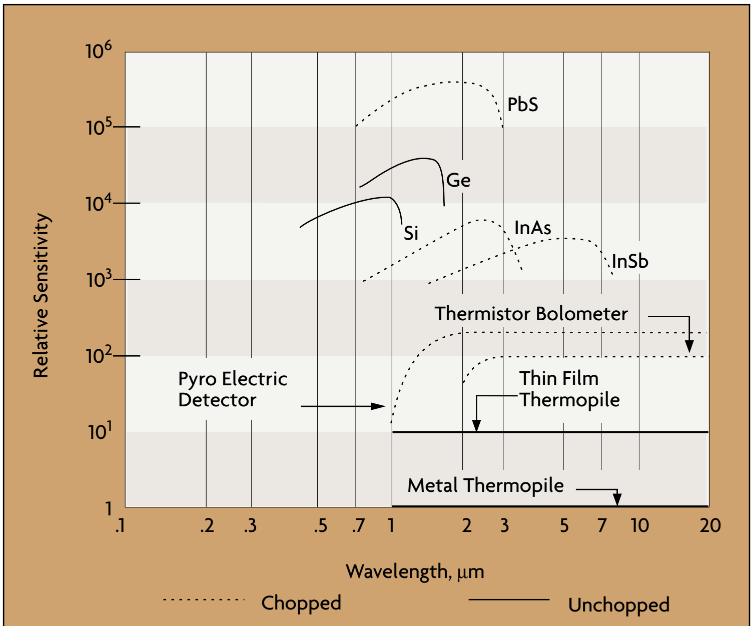

Figure 3-10: Relative Sensitivity of IR Detectors

Figure 3-10 shows the different sensitivity for various radiation detectors. PbS has the greatest sensitivity, and the thermopile the least.

Optical Systems

As shown in Figure 3-11, the optical system of a radiation pyrometer may be composed of lenses, mirrors, or combinations of both. Mirror systems do not generally determine the spectral response of the instrument, as the reflectivity is not dependent on wavelength over the range used for industrial temperature measurement. A mirror system must be protected from dirt and damage by a window. Copper, silver and gold are the best materials for mirrors in the infrared range. Silver and copper surfaces should be protected against tarnish by a protective film.

The characteristics of the window material will affect the band of wavelengths over which the thermometer will respond. Glass does not transmit well beyond 2.5 microns, and is suited only for higher temperatures. Quartz (fused silica) transmits to 4 microns, crystalline calcium fluoride to 10 microns, germanium and zinc sulfide can transmit into the 8 to 14 micron range. More expensive materials will increase the transmission capability even more, as shown in Figure 3-12.

Windows and filters, placed in front of or behind the optical system, and which are opaque outside a given wavelength range, can alter the transmission properties greatly, and prevent unwanted wavelengths from reaching the detector.

Mirror systems are generally used in fixed focus optical instruments. Varying the focus of the instrument requires moving parts, which is less complicated in a lens system. The selection of lens and window material is a compromise between the optical and physical properties of the material, and the desired wavelength response of the instrument. The essential design characteristics of materials suitable for lenses, prisms, and windows include approximate reflection loss, and short and long wavelength cut-offs. Figure 3-13 shows the transmittance of some common materials as a function of wavelength. Chemical and physical properties may dictate choice of material to meet given operating conditions.

The aberrations present in a single lens system may not permit precise image formation on the detector. A corrected lens, comprised of two or more elements of different material, may be required.

The physical shape of the optical system, and its mounting in the housing, controls the sighting path. For many designs, the optical system is aligned to surface and measures surface temperature. This is satisfactory for sizable targets. Visual aiming accessories may be required for sighting very small targets, or for sighting distant targets. A variety of aiming techniques are available which include: simple bead and groove gun sights, integrated or detachable optical viewing finders, through-lens sighting, and integrated or detachable light beam markers.

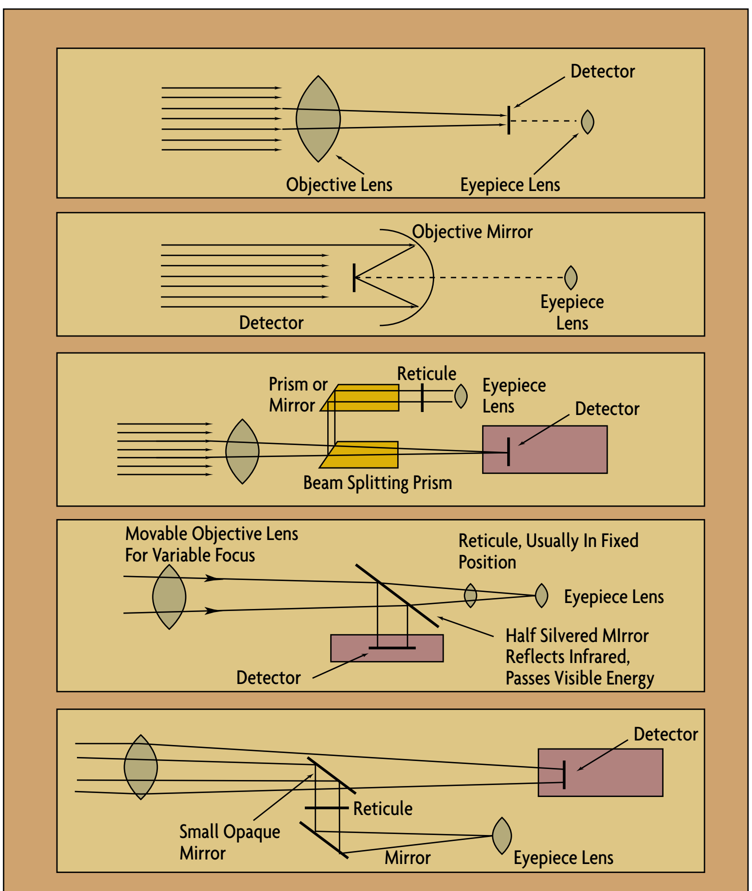

Figure 3-11: Typical Optical Systems

Field of View

The field of view of a radiation thermometer essentially defines the size of the target at a specified distance from the instrument. Field of view can be stated in the form of a diagram (Figure 3-14), a table of target sizes versus distance, as the target size at the focal distance, or as an angular field of view.

Figure 3-15 shows typical wide angle and narrow angle fields of view. With a wide angle field of view, target size requirements neck down to a minimum at the focal distance. The narrow angle field of view flares out more slowly. In either case, cross sectional area can vary from circular, to rectangular, to slit shaped, depending on the apertures used in the thermometer optics system.

Telescopic eyepieces on some designs can magnify the radiant energy so smaller targets can be viewed at greater distances. Targets as small as 1/16 inch in diameter are measurable using the correct thermometer design. A common optics system will produce a 1-inch diameter target size at a 15-inch working distance. Other optical systems vary from small spot (0.030 inch) for close up, pinpoint measurement, to distant optics that create a 3-inch diameter target size at 30 feet. The angle of viewing also affects the target size and shape.

In calibrating a radiation thermometer, the radiation source must completely fill the field of view in order to check the calibration output. If the field of view is not filled, the thermometer will read low. If a thermometer does not have a well defined field of view, the output of the instrument will increase if the object of measurement is larger than the minimum size.

The image of the field stop at the focal distance for most thermometers is larger than the diameter of the field stop. Between the focal distance, the field of view is determined by the lens diameter and the image diameter. Lines drawn from the image, at the focal distance, to the lens diameter enclose the field of view. Beyond the focal distance, the field of view is determined by rays extending from the extremities of the lens diameter through the extremities of the image at the focal distance.

In practice, any statement of field of view is only an approximation because of spherical and chromatic aberration. Spherical aberration is caused by the fact that rays hitting the lens remote from its axis are bent more than rays passing the lens near its axis. A circular field stop is imaged as a circle with a halo around it. Mirrors also have spherical aberration.

Chromatic aberration occurs because the refractive index of optical materials changes with wavelength, with the refractive index lower at shorter wavelengths. This means rays of shorter wavelength are bent more and focus nearer the lens, while rays of longer wavelength are focused farther from the lens. The image of a field stop over a band of wavelengths is hence a fuzzy image.

Fuzziness of the field of view can also be caused by imperfections in the optical material, and reflections from internal parts of the thermometer. Quality materials, and blackening of inside surfaces reduce these latter effects.

Some manufacturers state a field of view that includes effects of aberrations, and some do not. If the target size and stated field of view are nearly the same, it may be wise to determine the field of view experimentally. Sight the thermometer on a target that gives a steady, uniform source of radiation. At the focal distance, interpose a series of apertures of different diameter. Plot the thermometer output versus the aperture area. The output of the thermometer should increase proportional to the aperture area for aperture areas less than the nominal target area. The output should increase only minimally for increasing areas, above the nominal target area. Increases of a few tenths of a percent in output for each doubling of the aperture area indicates the nominal field of view takes into account the effects of aberrations. If these are not taken into account, the thermometer output may show significant increases in output as the viewable target area is increased above the nominal value.

Electronics

The calibration curves of detector output versus temperature of all detectors is non-linear because the equations relating the amount of radiation emitted by an object are power functions. The radiation thermometer electronics must amplify, regulate, linearize and convert this signal to an mV or mA output proportional to temperature.

Before microprocessors, the advantage of high N values was offset by the fact that the useful range of temperature measurement with an

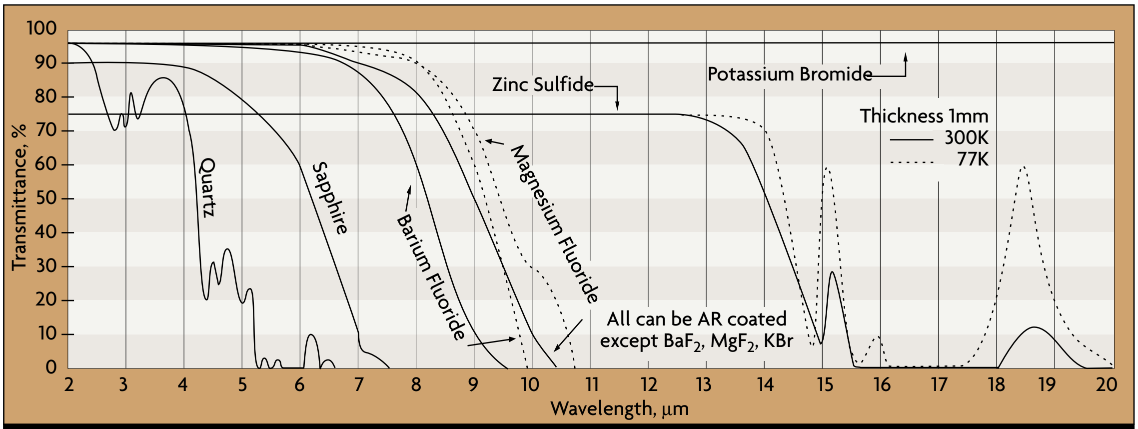

Figure 3-12: IR Transmission of Optical Materials

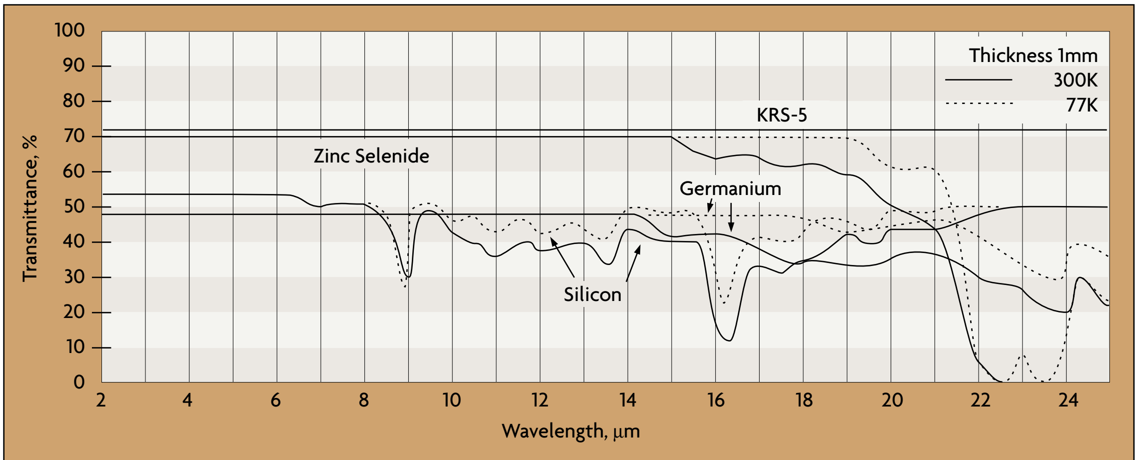

Figure 3-13: IR Transmission Characteristics

instrument of fixed span was very low. For example, for N=15, an instrument reading 100% of scale at 1000°C would read approximately 820°C at 10% of full scale. If the target temperature were expected to fall outside this narrow band, linearization or range switching was necessary. Today, microprocessors easily permit such signals to be linearized very cost effectively.

Microprocessor-based electronics (Figure 3-16) are superior to conventional analog electronics because in situ computing can be used to correct detector imperfections, provide emissivity compensation, and provide digital outputs for two way communications between the thermometer and a PC or a control system workstation.

Many of the shortcomings of thermal type detectors can be handled by sophisticated data processing techniques available in digital computers. The target temperature is an exponential function of the detector temperature. The output signal from the detector is a small voltage proportional to the difference in temperature between the target and the detector itself. To get the target temperature, it is necessary to accurately measure the detector temperature. Detector body temperatures span the range of the environment, from -50 to 100°C. Over this range, the most precise and accurate temperature transducer is the thermistor. However, thermistor outputs are highly non-linear and vary widely from unit to unit. Analog devices must abandon use of the thermistor for a less accurate and easier to use element, such as an integrated circuit, which has a linear output. But highly non-linear responses are no problem for a computer, and units with microprocessors can employ thermistors.

Detector responsivity is also a non-linear function of the detector body temperature. It is typically grossly corrected in analog devices with a simple linear gain correction produced by a temperature sensitive resistor in the preamplifier feedback network. A microprocessor can use a complex algorithm for the detection body temperature to correct for changes in detector responsivity.

The net radiant target signal power impinging on the detector is highly non-linear with the target temperature, and for temperatures under 1000°F, it is also dependent on the detector temperature itself. Again, a microprocessor can make accurate compensation for both these effects.

There is a fourth power relationship between the detector output voltage and target temperature. Analog devices typically use linear approximation techniques to characterize this relationship. A computer can solve, in real time, a complex algorithm, with as many as seven terms, instead of linear approximation, for higher accuracy.

Detector zero drift due to ambient temperature conditions can also be corrected using a microprocessor. This avoids errors of several degrees

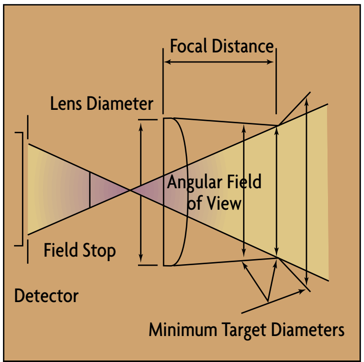

Figure 3-14: Field of View

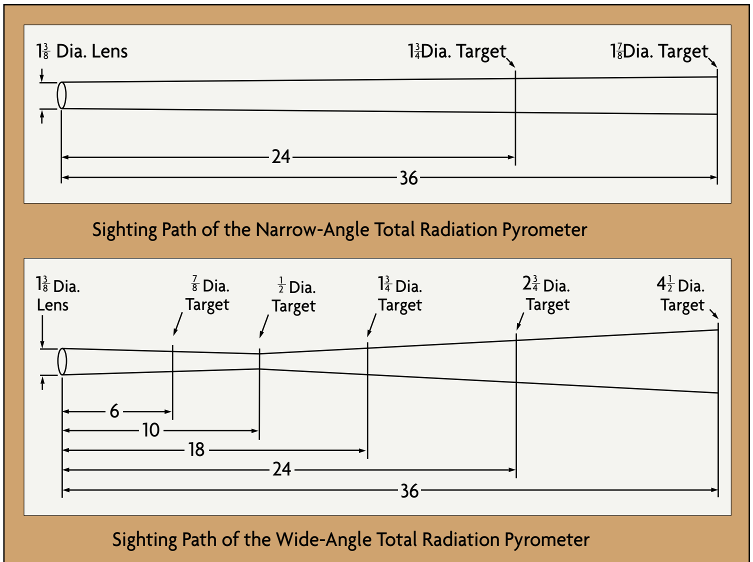

Figure 3-15: Typical Narrow and Wide Angle Sighting Paths

when you move an instrument from one room to another having a different temperature.

Precise emissivity corrections can be called up, either from as many as 10 values stored in EEPROM, or from a complex real-time algorithm dependent on target time-temperature relationships. An example is a program to compensate for the emissivity of a piece of steel, which oxidizes as it heats to higher temperatures.

Preprocessing by an onboard microprocessor may allow extraction of only the pertinent data needed by control systems. For example, only out of range data, determined by setpoints programmed into the microprocessor, may be desired for data transmission. This data can be transmitted digitally, on a priority interrupt basis. This is more efficient than having the user transmit all measured data to the host system, only to have the pertinent information sorted there.

An intelligent radiation thermometer can be programmed to run preprogrammed internal calibration procedures during gaps, or windows in measurement activity. This prevents internal calibration checks from taking the device off-line at a critical moment in the process. A thermometer reading the temperature of cans on a conveyor belt can run an internal calibration program whenever a gap between successive cans is sensed.

An internal microprocessor can also perform external control functions on external loop elements, using contact closure or relay outputs provided as options, and based on the incoming temperature data. In addition, intelligent devices can accept auxiliary inputs from thermocouples, RTDs or other radiation thermometers, and then use this data to support internal functions. For example, a high temperature setpoint could be continuously, and automatically reset by the microprocessor in response to input variable history.

A sample-and-hold function is useful when a selected event serves to trigger the temperature measurement of an object. The thermometer measures temperature at that instant, disregarding earlier or later measurements. Analog circuitry exhibited a slow drift of the measurement during the hold period, but modern digital instruments hold the value without degradation for indefinite periods.

Sometimes, the highest temperature within the field of view is of interest during a given period. Intelligent electronics can be programmed to store into memory the highest temperature it saw in a sampling period. This is called peak picking. Valley picking, when the lowest temperature measured over a given period is of interest, also is possible.

Averaging is used to prevent rapid excursions of the object temperature

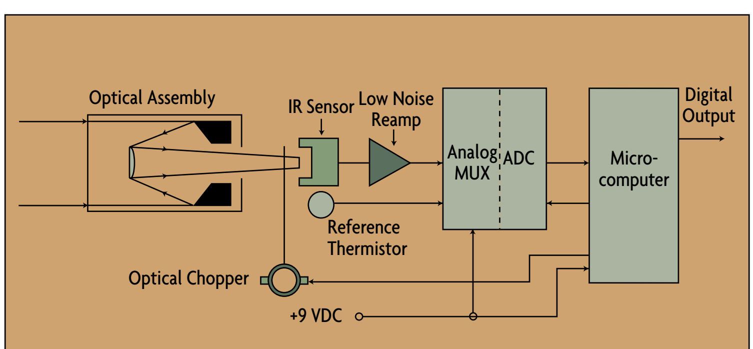

Figure 3-16: Microprocessor-Based IR Thermometer

from the average value from causing noise in the control system. A common way to accomplish this is to slow down the response of the instrument via software in the microprocessor-based electronics.

Construction

Figure 3-11, p. 33, illustrates the common types of construction found in industrial radiation thermometers. The constructions in (a) and (b) are typical of instruments using detectors that give a stable DC millivolt output without preamplification such as thermopiles and silicon cells. The construction in (a) has also been used for detectors whose DC drift demands that they be used in an AC mode. A spinning disk or vibrating reed is interposed between the lens and the detector to cyclically interrupt the radiation. Thus the detector sees pulses of radiation. The output of the detector is AC. The detector package must be small enough so that it doesn't interfere with optical sighting to the target.

The constructions in (c), (d), and (e) are useful when the detector package is too large to permit sighting around it. Optical chopping between the lens and the detector is common in these constructions. The back surface of the chopping disk, or blade, may serve as a local ambient temperature reference. The detector alternately sees the target and the modulating device, which is at local ambient temperature.

In some designs, a local hot source, or hot surface, may be maintained at a known reference temperature. The detector alternately sees the target and the reference source. The resulting AC signal can then be calibrated in terms of the unknown target temperature.

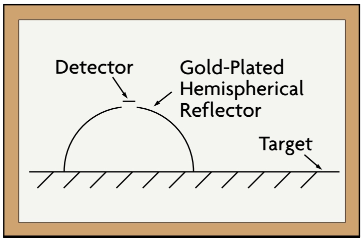

Figure 3-17: Surface Temperature Pyrometer

In ratio thermometers, the filters that define the pass band of the two radiation signals that are ratioed may be on the chopping disc.

Figure 3-17 illustrates a portable radiation thermometer for spot measurement of the temperature of a surface. Radiation from the target is multiply reflected from the hemispherical mirror shown. A detector receives this radiation through a small opening in the reflector. The radiation multiply reflected between the mirror and target appears to the detector to be from a blackbody. A commercial pyrometer using this technique can read the temperature of targets with emissivity as low as 0.6 without correction. The reflector must be placed close to the surface being measured to eliminate extraneous radiation and prevent losses. It can only be used for short time durations because heating of the reflector will affect the measurement accuracy. In addition, the energy reflected back to the target surface may cause its temperature to change. T

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Infrared Thermocouples

As described in chapter 3 on "IR Thermometers & Pyrometers", thermocouples have been used as detectors in radiation thermometry for many decades. Often, a series of thermocouples, or thermopile, was the thermal detector of choice. But in more recent years a new class of low-cost, self-powered "infrared thermocouples" has been developed, and has opened up a broad market for non-contact temperature measurement in such industries as food, electronics, paper, pharmaceutical, plastics, rubber, and textiles.

All infrared thermocouple sensors work in a fashion similar to a standard thermocouple: a small millivoltage or electromotive force (emf) relates to the temperature being measured. To correctly apply any such instrument, the user or designer must be aware of certain basic characteristics of all thermocouples and the circuitry involved. Just how does the thermocouple function in providing a usable emf measuring signal? And what is important to observe so far as metering that signal to accurately indicate the measured temperature? What is the effect of changes in ambient temperature—at the thermocouple and at the meter? A discussion with reference to Figure 4-1 will help make such points clear.

Thermocouple Basics

Let's start with T. J. Seebeck, who in 1821 discovered what is now termed the thermoelectric effect. He noted that when two lengths of dissimilar metal wires (such as iron and Constantan) are connected at both ends to form a complete electric circuit, an emf is developed when one junction of the two wires is at a different temperature than the other junction.

Basically, the developed emf (actually a small millivoltage) is dependent upon two conditions: (1) the difference in temperature between the hot junction and the cold junction. Note that any change in either junction temperature can affect the emf value and (2) the metallurgical composition of the two wires.

Although a "thermocouple" is often pictured as two wires joined at one end, with the other ends not connected, it is important to remember that it is not a true thermocouple unless the other end is also connected! It is well for the user to remember this axiom: "Where there is a hot junction there is always a cold or reference junction" (even though it may seem hidden inside an instrument 1,000 feet away from the hot junction).

Still in Seebeck's century, two other scientists delved deeper into how the emf is developed in a thermoelectric circuit. Attached to their names are two phenomena they observed—the Peltier effect (for Jean Peltier in 1834) and the Thompson effect (for Sir William Thompson a.k.a Lord Kelvin in 1851). Without getting into the theories involved, we can state that the Peltier effect is the emf resulting solely from the contact of the two dissimilar wires. Its magnitude varies with the temperature at the juncture. Similarly, the Thompson effect can be summarized as having to do with emf's produced by a temperature gradient along a metal conductor. Since there are two points of

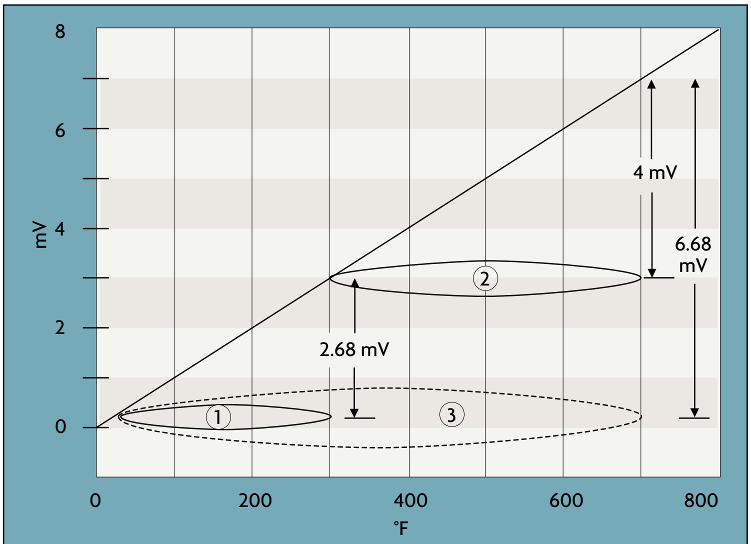

Figure 4-1: Thermocouple Operation

contact and two different metals or alloys in any thermocouple, there are two Peltier and two Thompson emfs. The net emf acting in the circuit is the result of all the above named effects.

Polarity of the net emf is determined by (a) the particular metal or alloy pair that is used (such as iron-constantan) and (b) the relationship of the temperatures at the two junctions. The value of the emf can be measured by a potentiometer, connected into the circuit at any point.

In summary, the net emf is a function primarily of the temperature difference between the two junctions and the kinds of materials used. If the temperature of the cold junction is maintained constant, or variations in that temperature are compensated for, then the net emf is a function of the hot junction temperature.

In most installations, it is not practical to maintain the cold junction at a constant temperature. The usual standard temperature for the junction (referred to as the "reference junction") is 32°F (0°C). This is the basis for published tables of emf versus temperature for the various types of thermocouples.

The Law of Intermediate Temperatures provides a means of relating the emf generated under ordinary conditions to what it should be for the standardized constant temperature (e.g., 32°F). Referring to Figure 4-1, which shows thermocouples 1 and 2 made of the same two dissimilar metals; this diagram will provide an example of how the law works. Thermocouple 1 has its cold junction at the standard reference temperature of 32°F and its hot junction at some arbitrary intermediate reference temperature (in this case, 300°F). It generates 2.68 mv. Thermocouple 2 has its cold junction at the intermediate reference point of 300°F and its hot junction at the temperature being measured (700°F). It generates 4.00 mv. The Law of Intermediate Temperatures states the sum of the emfs generated by thermocouples 1 and 2 will equal the emf that would be generated by a single thermocouple (3, shown dotted) with its cold junction at 32°F and its hot junction at 700°F, the measured temperature. That is, it would hypothetically read 6.68 mv and represent the "true" emf according to the thermocouple's emf vs. temperature calibration curve.

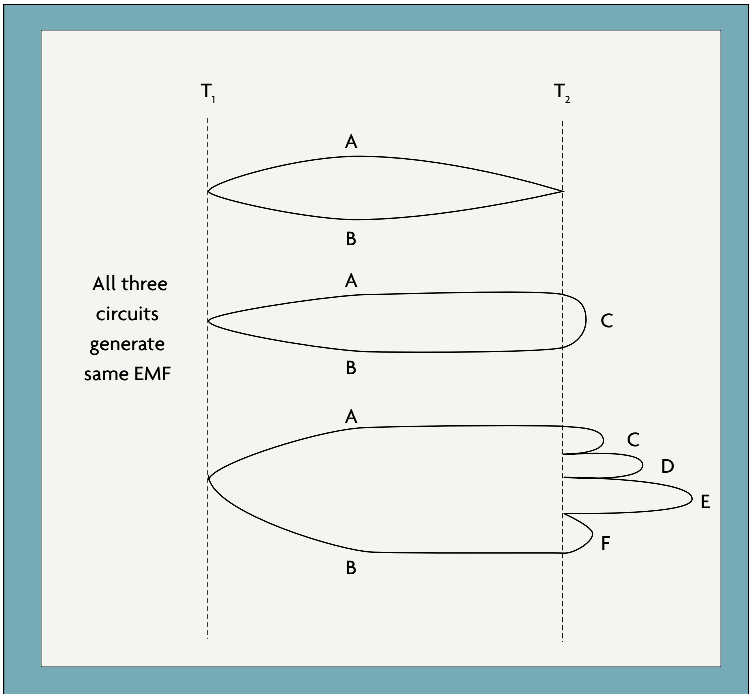

Figure 4-2: Equivalent Thermocouple Circuits

Based upon this law, the manufacturer of an infrared thermocouple need only provide some means of substituting for the function of thermocouple 1 to provide readings referenced to the standard 32°F cold junction. Many instruments accomplish this with a temperature-sensitive resistor which measures the variations in temperature at the cold junction (usually caused by ambient conditions) and automatically develops the proper voltage correction.

Another use of this law shows that extension wires having the same thermoelectric characteristics as those of the thermocouple can be introduced into the thermocouple circuit without affecting the net emf of the thermocouple.

In practice, additional metals are usually introduced into the thermocouple circuit. The measuring instrument, for example, may have junctures that are soldered or welded. Such metals as copper, manganin, lead, tin, and nickel may be introduced.

Would not additional metals like this modify the thermocouple's emf? Not so, according to the Law of Intermediate Metals. It states that the introduction of additional metals will have no effect upon the emf generated so long as the junctions of these metals with the two thermocouple wires are at the same temperature. This effect is illustrated in Figure 4-2, with A and B representing the thermocouple wires.

A practical example of this law is found in the basic thermoelectric system shown in Figure 4-3. The instrument can be located at some distance from the point of measurement where the thermocouple is located. Several very basic and practical points are illustrated in this elementary circuit diagram:

Quite often the most convenient place to provide the cold junction compensation is in the instrument, remote from the process.

With the compensation means located in the instrument, in effect, the thermoelectric circuit is extended from the thermocouple hot junction to the reference (cold) junction in the instrument.

The actual thermocouple wires normally terminate relatively near the hot junction. Conventional couples have what is called a "terminal head" at which point interconnecting wires, known as "extension wires" are required as shown. Since these wires are in the thermoelectric circuit, they must essentially match the emf vs. temperature characteristics of the thermocouple.

With the cold junction located inside the instrument, internal extension wires of the proper materials must be used between the instrument terminals and the cold junction.

With this set-up, there are in effect three added thermocouples in the circuit: one in the thermocouple assembly, one in the external extension wire, and in the internal extension wire. However, according to the Law of Intermediate Temperatures, the actual temperatures at the terminal head and at the instrument terminals is of no consequence: the net effect of the three thermocouples is as if one thermocouple ran from the hot junction to the cold junction.

The Infrared Thermocouple

Over the past decade or two, there has been a mushroom growth in the small, application-specific designs of infrared thermocouples. These contain a sophisticated optical system and electronic circuitry that belie the simplicity of their external, tube-like appearance. They use a special proprietary design of thermopile which develops enough emf to be connected directly to a conventional thermocouple type potentiometer or transmitter for all types of indication, recording, and control.

A wide variety of these devices are commercially available, covering temperature ranges from -50 to 5000°F (-45 to 2760°C) with up to 0.01°C precision. The range of models includes:

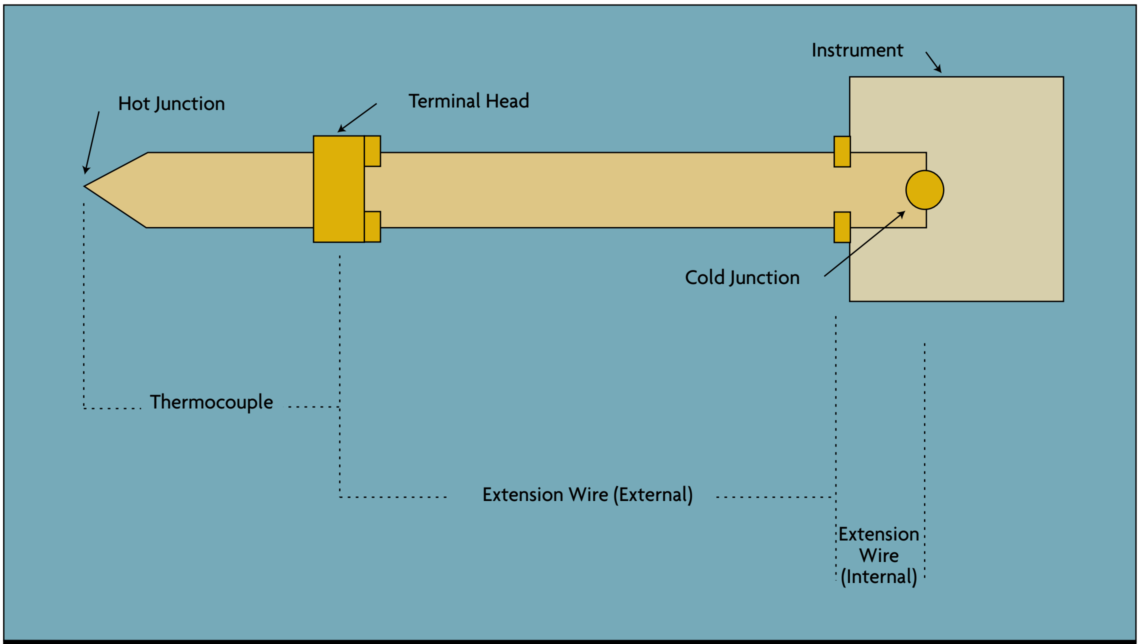

Figure 4-3: Typical Thermocouple Installation

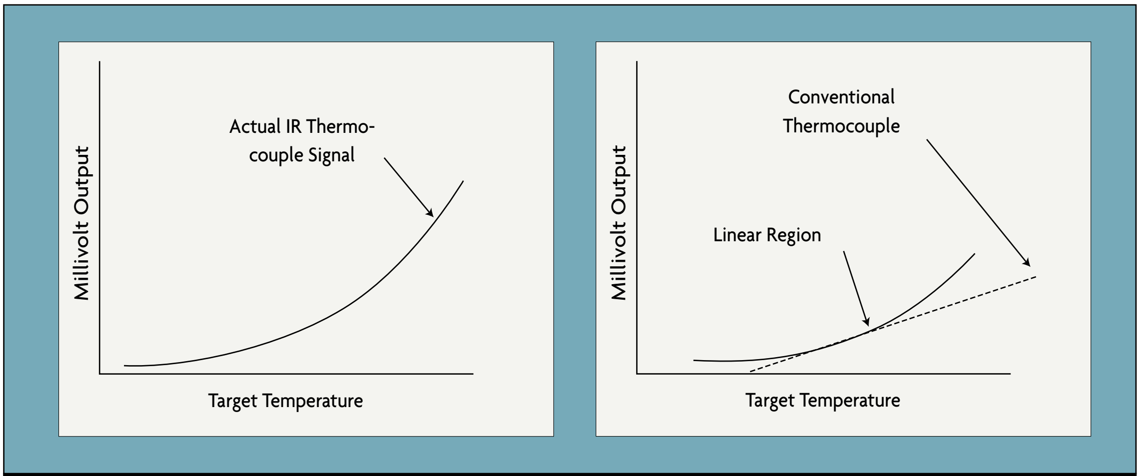

Figure 4-4: IR Thermocouple Output

- Standard units, simulating the thermocouple outputs J, K, T, E, R, and S and offering 12 different fields of view from 1:2 to 100:1. Minimum spot size is 1 mm and focused spot sizes available range from 4 mm to 12 mm.
- Handheld scanning models for such applications as accurate scanning of electrical equipment and NIST traceable surface temperature calibration—a must for ISO 9001, 9002, 9003 programs.
- Thermal switches that act like photocells for use in production line quality inspection of thermal processes with line speeds of up to 1000 feet per minute.

All infrared thermocouples are self-powered, using only the incoming infrared radiation to produce an mv output signal through thermoelectric effects. The signal thus follows the rules of radiation thermal physics and produces a curve as shown in Figure 4-4.

Over a specific, relatively narrow temperature range, the output is sufficiently linear to produce an mv output that can be closely matched to the mv vs. temperature curve of a given thermocouple type (Figure 4-4). What's more, the designer can match the two curves to be within a degree of tolerance such as ±2%, as specified by the buyer.

Each model is specifically designed for optimum performance in the region of best linear fit with the thermocouple's mv vs. temperature curve. The sensor can be used outside that range, however, by simply calibrating the readout device appropriately. Once so calibrated, the output signal is smooth and continuous over the entire range of the thermocouple, and will maintain a 1% repeatability over the entire range.

The user can select a model to provide, say, a 2% accuracy, by referring in the supplier's literature to a Range Chart which provides a vertical list of "Range Codes" with a corresponding Temperature Range over which 2% accuracy is to be expected. The user also specifies the type of thermocouple (J, K, etc).

A typical infrared thermocouple comprises a solid, hermetically-sealed, fully-potted system. As such, even during severe service, it does not change either mechanically or metallurgically. It contains no active electronic components and no power source other than the thermocouple itself. Thus, suppliers rate its long-term repeatability, conservatively, at 1%.

Long term accuracy is influenced by the same factors that affect reliability. In comparison to the application of conventional thermocouples, the infrared thermocouple is well protected inside a rigid, stainless steel housing. Along with the solid, fully-potted construction, this design essentially eliminates the classical drift problems of conventional thermocouples. Double annealing at temperatures above 212°F (100°C) helps ensure long term stability.

Installation Guidelines

Like all radiation-based sensing systems, the infrared thermocouple must be calibrated for specific surface properties of the object being measured, including amount of heat radiated from the target surface and environmental heat reflections.

The calibration is performed by measuring the target surface temperature with a reliable independent surface-temperature probe. One such device is a handheld infrared thermometer with a built-in automatic emissivity compensation system.

The following procedure is recommended:

(1) Install the infrared thermocouple as close as practical to view the target to be measured.

(2) Connect the infrared thermocouple to the supervisory controller or data acquisition system in standard fashion (including shield). As with conventional thermocouples, the red wire is always negative.

(3) Bring the process up to normal operating temperature and use the hand-held radiation thermometer to measure the actual target temperature.

(4) Make the proper adjustments on the readout instrument so that its calibration matches the reading of the handheld device. T

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Fiber Optic Extensions

Fiber optics are essentially light pipes, and their basic operation may be traced back more than a century when British Physicist John Tyndall demonstrated that light could be carried within a stream of water spouting out and curving downward from a tank. A thin glass rod for optical transmission was the basis of a 1934 patent awarded to Bell Labs for a "Light Pipe." American Optical demonstrated light transmission through short lengths of flexible glass fibers in the 1950s. However, most modern advances in fiber optics grew out of Corning Glass developments in glass technology and production methods disclosed in the early 1970s.

Like many technical developments since WWII, fiber optics programs were largely government funded for their potential military advantages. Projects primarily supported telecommunications applications and laser fiber ring gyroscopes for aircraft/missile navigation. Some sensor developments were included in manufacturing technology (Mantech) programs as well as for aircraft, missile and shipboard robust sensor developments. More recently the Dept. of Energy and NIST have also supported various fiber optic developments.

Commercial telecommunications has evolved as the fiber optics technology driving force since the mid-'80s. Increased use of fiber optics well correlates with fiber materials developments and lower component costs. Advances in glass fibers have led to transmission improvements amounting to over three orders of magnitude since the early Corning Glass efforts. For example, ordinary plate glass has a visible light attenuation coefficient of several thousand dBs per km. Current fiber optic glasses a kilometer thick would transmit as much light as say a ¼" plate glass pane. Table 5-1 indicates relative digital data transmission losses for copper and fiber.

Fiber Advantages

Improved glass transmissions have resulted in undersea cables with repeaters required about every 40 miles—ten times the distance required by copper. Bandwidth and robustness have led to cable service providers selecting fiber optics as the backbone media for regional multimedia consumer services. The world market for fiber optic components was in the $4 billion range in 1994 and is projected to reach $8 billion in 1998.

Whether used for communications or infrared temperature measurement, fiber optics offer some inherent advantages for measurements in industrial and/or harsh environments:

- Unaffected by electromagnetic interference (EMI) from large motors, transformers, welders and the like;
- Unaffected by radio frequency interference (RFI) from wireless communications and lightning activity;
- Can be positioned in hard-to-reach or view places;
- Can be focused to measure small or precise locations;
- Does not or will not carry electrical current (ideal for explosive hazard locations);
- Fiber cables can be run in existing conduit, cable trays or be strapped onto beams, pipes or conduit (easily installed for expansions or retrofits); and,
- Certain cables can handle ambient temperatures to over 300°C—higher with air or water purging.

Any sensing via fiber optic links requires that the variable cause a

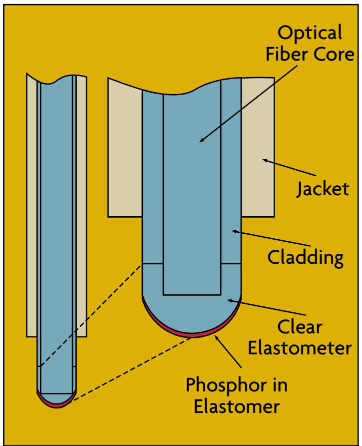

Figure 5-1: Fiber Optic Probe Construction

Table 5-1: Relative Transmission Losses for Digital Data

	Losses in dB/km		
	1.5Mb/s	6.3Mb/s	45Mb/s
26 gage twisted wire pair	24	48	128
19 gage twisted wire pair	10.8	21	56
RG 217/u coaxial cable	2.1	4.5	11
Optical fiber 0.82 μm wavelength carrier	3.5	3.5	3.5

modulation of some type to an optical signal—either to a signal produced by the variable or to a signal originating in the sensing device. Basically, the modulation takes the form of changes in radiation intensity, phase, wavelength or polarization. For temperature measurements, intensity modulation is by far the most prevalent method used.

The group of sensors known as fiber optic thermometers generally refer to those devices measuring higher temperatures wherein blackbody radiation physics are utilized. Lower temperature targets—say from -100°C to 400°C—can be measured by activating various sensing materials such as phosphors, semiconductors or liquid crystals with fiber optic links offering the environmental and remoteness advantages listed previously.

Fiber Applications

Fiber optic thermometers have proven invaluable in measuring temperatures in basic metals and glass productions as well as in the initial hot forming processes for such materials. Boiler burner flames and tube temperatures as well as critical turbine areas are typical applications in power generation operations. Rolling lines in steel and other fabricated metal plants also pose harsh conditions which are well handled by fiber optics.

Typical applications include furnaces of all sorts, sintering operations, ovens and kilns. Automated welding, brazing and annealing equipment often generate large electrical fields which can disturb conventional sensors.

High temperature processing operations in cement, refractory and chemical industries often use fiber optic temperature sensing. At somewhat lesser temperatures, plastics processing, paper making and food processing operations are making more use of the technology. Fiber optics are also used in fusion, sputtering, and crystal growth processes in the semiconductor industry.

Beyond direct radiant energy collection or two-color methods, fiber optic glasses can be doped to serve directly as radiation emitters at hot spots so that the fiber optics serve as both the sensor and the media. Westinghouse has developed such an approach for distributed temperature monitoring in nuclear reactors. A similar approach can be used for fire detection around turbines or jet engines. Internal “hot spot” reflecting circuitry has been incorporated to determine the location of the hot area.

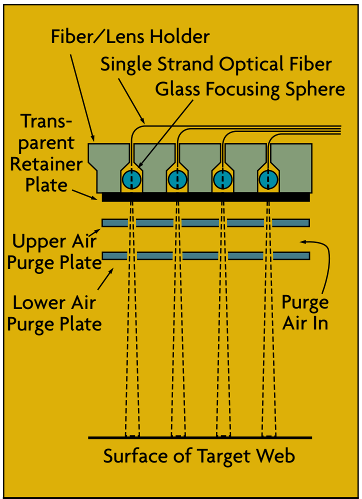

Figure 5-3: Multipoint Pick-up Assembly

An activated temperature measuring system involves a sensing head containing a luminescing phosphor attached at the tip of an optical fiber (Figure 5-1). A pulsed light source from the instrument package excites the phosphor to luminescence and the decay rate of the luminescence is dependent on the temperature. These methods work well for non-glowing, but hot surfaces below about 400°C.

A sapphire probe developed by Accufiber has the sensing end coated by a refractory metal forming a blackbody cavity. The thin, sapphire rod thermally insulates and connects to an optical fiber as is shown in Figure 5-2. An optical interference filter and photodetector determines the wavelength and hence temperature.

Babcock & Wilcox has developed a quite useful moving web or roller temperature monitoring system

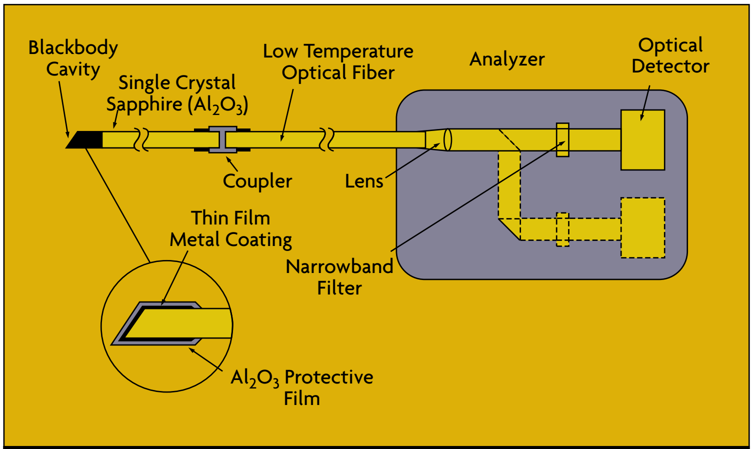

Figure 5-2: Typical IR Fiber Optic Probe

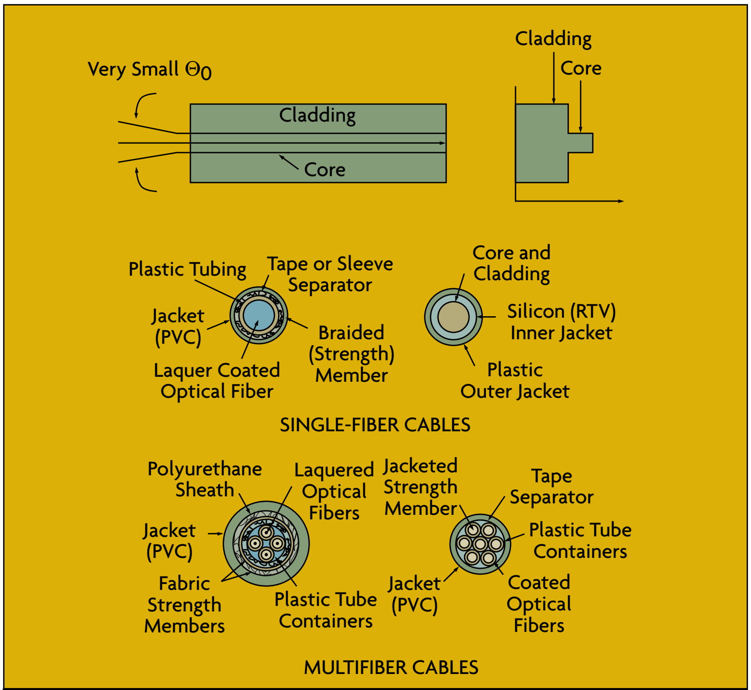

Figure 5-4: Fiber Optic Cable Construction

which will measure temperatures from 120°C to 180°C across webs up to 4 meters (13 ft.) wide (Figure 5-3). The system combines optical and electronic multiplexing and can have as many as 160 individual pickup fibers arranged in up to 10 rows. The fibers transfer the radiation through a lens onto a photodiode array.

Component Options

Fiber optics for temperature measurements as well as for communications depends on minimizing losses in the light or infrared radiation being transmitted. Basics of light conduction (Figure 5-4) is a central glass fiber which has been carefully produced to have nearly zero absorption losses at the wavelengths of interest. A cladding material with a much lower index of refraction reflects all non-axial light rays back into the central fiber core so that most of the conducted radiation actually bounces down the length of the cable. Various metal, Teflon or plastics are used for outer protective jackets.

The difference in refractive indices of the core and cladding also identify an acceptance cone angle for radiation to enter the fiber and be transmitted. However, lenses are often used to better couple the fiber with a target surface.

For relatively short run temperature sensing, losses in the fiber optic link are generally negligible. Losses in connectors, splices and couplers predominate and deserve appropriate engineering attention. Along with the fiber optic cable, a temperature measuring system will include an array of components such as probes, sensors or receivers, terminals, lenses, couplers, connectors, etc. Supplemental items like blackbody calibrators and backlighter units which illuminate actual field of view are often needed to ensure reliable operation. T

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Linescanning & Thermography

Linescannning and thermography essentially extend the concept of point radiation thermometry to one-dimensional profiles or two-dimensional pictures of non-contact temperature data.

One-dimensional linescanners have a wide range of application. They are used in the production of fiberboard, carpets, vinyl flooring, paper, packaging material, pressure sensitive tapes, laminates, float glass, safety glass, and nearly any other web-type product for which temperature control is critical. Linescanners also monitor hot rolling mills, cement and lime kilns, and other rotary thermal processing equipment.

Thermographic "cameras" find use in the maintenance function in manufacturing plants, especially in the asset-driven capital intensive industries in which temperature is an active concern and diagnostic tool. Typical targets for infrared inspection include electrical equipment, frictional effects of power transmission equipment, and thermal processing steps in a production line.

Infrared Linescanners

The typical sensor unit for linescan thermography uses a single detector that, by itself, is limited to measuring the temperature at only one point. However, a rotating mirror assembly focuses a single, constantly changing, narrow slice of real-world view on the detector surface (Figure 6-1).

Although adequate thermal measurement resolution may require only a few dozen scans per second, contemporary units offer up to 500 scans per second. The electronic circuitry behind the detector element chops the thermal data for each linear pass into several hundred to several thousand individual measurement points. High speed data collection circuitry then quantifies, digitizes, and captures the temperature of the object at the measurement points along each scan. Additional circuitry then analyzes and manipulates the digital data to produce a real-time display of the temperature of the view presented to the detector.

By itself, a linear temperature scan constitutes a rather myopic view of a stationary object. However, an object moving past a stationary linescanner provides a data-rich measuring environment. Mounted several feet above and focused on the moving web of product in a production line makes the linescanner an element of a real-time process feedback and closed-loop control scheme.

Linescanner Operation

The resolution of a linescanner is a function of the speed of the moving web, the scan rate, the number of measurements per scan, and the width of the scanned line. The accuracy and response of the linescanner depends on a clean optical path between the target and the overhead detector, which can be problematic in a typical manufacturing environment. Linescanners are available with

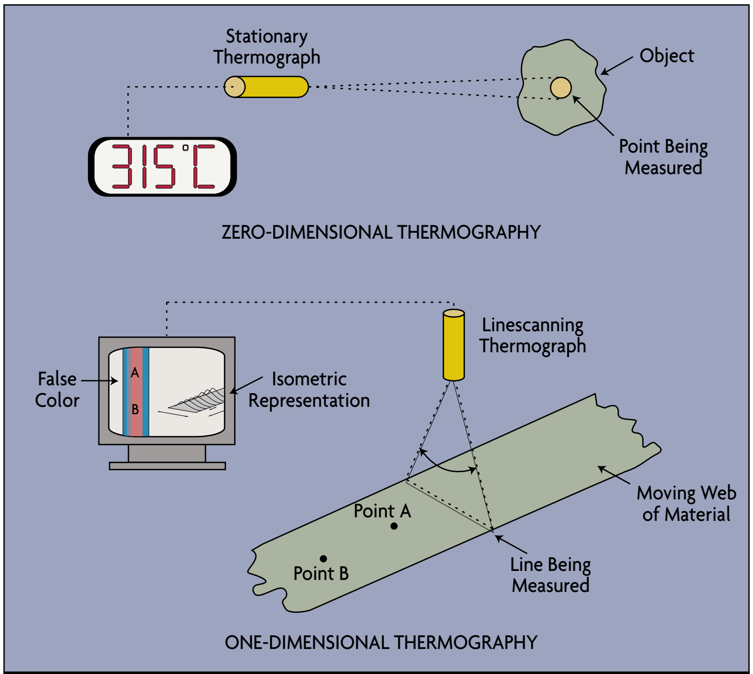


Figure 6-1: Linescanner Operation

air purge system to keep the optics clean. Water cooling of the sensor assembly may be necessary to maintain reliable operation in hot environments. Sealed housings and bearings protect delicate components against moisture and dust.

The digital electronic output from the linescanner typically feeds a personal computer running software that converts the stream of data into a real-time moving image of the web passing the detector assembly. Because the human retina is not sensitive to infrared radiation, the screen image is necessarily rendered in false color the hue of which corresponds to the temperature of the specific location.

The linescan output converts the traditional plot of temperature versus time into a three-axis measurement of temperature as a function of time and location across the web of material (Figure 6-2). The scanner "maps" the "thermal terrain" moving below the detector assembly. As is typical of false color thermographic output, the electronics assigns the color of a given screen pixel on the basis of the temperature implied by the measured infrared radiation.

• Linescanner Applications

Linescanning technology offers industry an opportunity to optimize thermally-based processes. For example, plastic thermoforming fabrication requires heating a plastic sheet using an array of heaters. The temperature is critical if the vacuum molding process is to successfully form pleats, deeply drawn recesses, and sharp corners in the completed piece part. A high-resolution linescanner, used in a closed-loop configuration to control the output of the individual heaters, helps to maximize the productivity of the press.

Another application for linescanning in the plastic industry is in blow-molding plastic film. The process involves extruding a polymer melt through a circular die and drawing the formed tube upward. At some point as the plastic rises it solidifies at what is called the frost line. Additional cooling must occur so that the plastic sheeting achieves the proper temperature as it enters the overhead takeup rolls.

Maintaining a proper temperature profile of the moving plastic is critical to eliminating functional and aesthetic defects in the sheeting. Mounting a scanner to monitor the rising plastic gives the operators instant information about the precise location of the frost line and other temperature-related information in real-time.

A similar approach is used in the glass industry. Glass sheets are heat treated to give them the required strength. As the glass moves on a conveyor belt, electric heaters raise its temperature as uniformly as possible. After a suitable holding time in the oven, the glass sheet is cooled uniformly with compressed air. In this process are all the elements of a linescanner application for a moving web of temperature sensitive material.

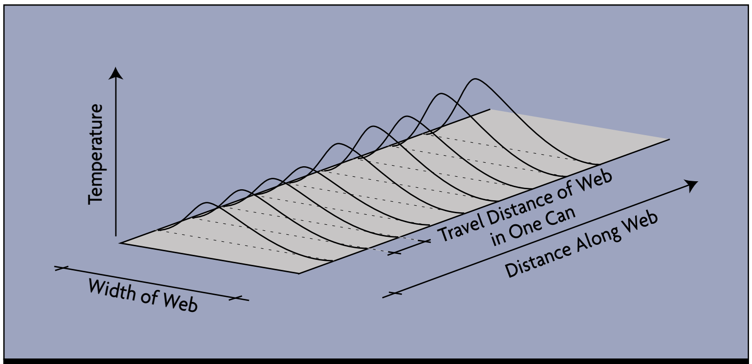


Figure 6-2: 1-D Scans Composited Into a 2-D Image

2-D Thermographic Analysis

Adding another simultaneous geometric dimension to the linescanning concept leads to the practices of two-dimensional thermographic analysis. Two-dimensional figures are planes exhibiting only length and width but no height. The two-dimensional plane in question is the view you see with your own eyes. The thermographic equipment in question is an infrared camera comparable in size to a video camera (Figure 6-3).

Devices used for thermographic analysis generally fall into two broad classes. Radiometry devices are used for precise temperature measurement. The second, called viewing devices, are not designed for quantitative measurements but rather for qualitative comparisons. A viewer only tells you that one object is warmer than another, whereas radiometry tells you that one object is, for instance, 25.4 degrees warmer than the other with an accuracy in the neighborhood of 2 degrees or 2 percent.

Whereas a standard video camera responds to visible light radiating from the object in view, thermographic units responds to the object's infrared radiation. The scene through the camera's viewfinder is presented in false colors designed to convey temperature information.

Specular surfaces, especially metallic ones, reflect infrared radiation. The image of a shiny metal surface viewed through an infrared camera contains thermal information inherent to and radiated by the surface as well as thermal information about the surroundings reflected by the surface. When monitoring the temperature of a transparent object, the optical system may pick up a third source of radiation—that transmitted through from objects on the other side. Modern imagers have emissivity controls that adjust the response of the unit so that it reads accurately. (See p. 72 for emissivity tables of common materials.)

The compact size of thermographic imagers eliminates the need for tripods and other factors that limit mobility. In fact, in an industrial setting, the technician using the handheld imager may well be reading temperatures or capturing images while walking around. Doing so can be dangerous since the user's attention is on data collection and not on environmental trip hazards. For that reason, imagers do not have the typical "eyepiece" found on a video cameras. Imagers use, instead, a 4-inch flat panel display, typically a color liquid crystal display.

Detectors Options

The earliest thermal imaging systems featured a single detector and a spinning mirror that scanned the image coming through the lens of the camera and focused the pixels of the two-dimensional image on the detector in sequence. The electronics that captures data is synchronized with the mirror so that no thermal information is lost or garbled. One of the problems with the single detector approach is dwell time. Scanning a 120 x 120 pixel image with a spinning mirror does not give any single pixel very much time to register a reading on the detector.

The newest thermal imaging systems eliminate the need for the spinning mirror by replacing the single point detector with a solid-state detector that continuously "stares" at the entire image coming through the lens. Dwell time is no longer an issue because the scene coming through the optics maps directly on the active surface of the focal plane array detector. Using the focal plan array technology brings several benefits to the user.

The most obvious benefit is fewer moving parts in the camera. Fewer parts leads to higher reliability and almost certainly higher durability against physical abuse and other hazards of the workplace. The newer thermal imagers are smaller and lighter than their predecessors. In fact, the latest infrared imagers are of a size not much larger than the smallest of the modern handheld video camera.

The resolution of the focal plan array—a minimum of 320 x 244 pixels—is much greater than that offered by the single detector models. A finer resolution leads directly to being able to discern smaller "hot spots" in the field of view.

Detector Cooling

The detector in either type of imager must be cooled if it is to work properly. This is analogous to looking out of a window at night. If the room lights are on, it is difficult to see clearly because there is too much visible light coming from the room itself. Turning the lights off makes it much easier to see outside. Similarly, accurately measuring the temperature can be difficult if the camera parts surrounding the detector are giving off too much infrared radiation. A cooler detector is equivalent to turning off the lights in the room. Infrared imaging technology relies on a refrigerated detector. The earliest thermography cameras used liquefied gases to cool the detector. Certainly the technology was new and the operating refinements were crude. As you can imagine, the early units were not all that portable. The key element of contemporary radiometers is a sufficiently small, battery-operated Stirling cycle engine to keep the detectors cold.

There are two common methods for cooling the detector chip. A Stirling cycle engine provides the cryogenic cooling required by precise radiometry devices. Thermoelectric cooling provides the temperature stabilization required by a viewer. In cryogenic cooling, the detector is chilled to around -200°C, whereas temperature stabilization requires cooling the detector to somewhere near room temperature.

Depending on the design of the detector, the stabilization temperature may be in the range of 20 to 30° C or it may be at the Curie temperature in the range of 45-60°C. Operating at the Curie temperature offers better sensitivity to the incoming infrared radiation. In either case, the temperatures must be constant from reading to reading if the imager is to provide consistent and reproducible results. As an aside, in common industry parlance, units that rely on thermoelectric cooling are referred to as "uncooled" units relative to cryogenically cooled devices.

The Stirling Engine

In 1816, Robert Stirling developed what is called in thermodynamic terms a closed-cycle regenerable external combustion engine. This machine produces no waste exhaust gas, uses a diversity of heat sources to power it, remains quiet during operation, and has a high theoretical thermal efficiency. The Stirling cycle consists of four steps: heating at constant volume, isothermal expansion, cooling at constant volume, and isothermal compression (Figure 6-4). The device converts heat into its equivalent amount of mechanical work. In effect, one obtains shaft work by heating the engine. Fortunately, the Stirling cycle is a reversible thermodynamic process, and mechanical work can be used to produce a cooling effect.

This need for cooling is a limitation only in the sense that one cannot achieve true "instant on" with an infrared imager. Cryogenic cooling requires five to nine minutes to achieve the very low temperatures required for the detector to respond. Thermoelectric cooling, on the other hand takes about one minute or less.

Other Detector Developments

Soon, researchers are expected to produce less expensive uncooled radiometric detectors with sensitivity and resolution at least as good as today's cryogenic units. One of the problems to be surmounted is the relatively low yields in the detector manufacturing process. Until the production problems find a solution, the cost of the high-performance uncooled detectors will remain on a par with cryogenic units and their Stirling engines.

There is one true "instant on" unit that depends on pyroelectric arrays for the detector elements. These imagers require absolutely no cooling but they require a constantly changing image signal. If the scene presented to the lens does not change, the camera ceases to resolve any image at all. Imagers based on the pyroelectric principle are suitable for viewer use only, not radiometry. However, it is possible to use a point detector aligned with the centerline of the image to record one temperature to represent the entire frame. Because the pyroelectric element is piezoelectric, it generates an extraneous signal in response to vibration of the camera housing. Such sensitivity requires that the units be shock mounted to damp out the vibrations.

Spatial, Temperature Resolution

There are two types of thermographic detector resolution to be distinguished. First is spatial resolution. The detector assemblies in focal plane arrays have multiple detector elements on a single detector chip that map directly to the aperture of the optical system. High spatial resolution means the camera can distinguish between two closely spaced items. Temperature resolution refers to the ability of the camera to distinguish temperature differences between two items. Temperature resolution is a function of the type of detector element; spatial resolution is a function of the number of detector elements.

Specification sheets for infrared imagers give the spatial resolution in terms of milliradians of solid angle (Figure 6-5). The milliradian value is related to the theoretical object area covered by one pixel in the instantaneous field of view. Obviously, at greater distances more of the object area maps to a single pixel and a larger area means less precise thermal information about any single element in that larger area.

Applications of Thermography

An effective predictive maintenance program implies the need to collect sometimes rather sophisticated data from productive assets located around the plant floor. A plant maintenance technician normally follows

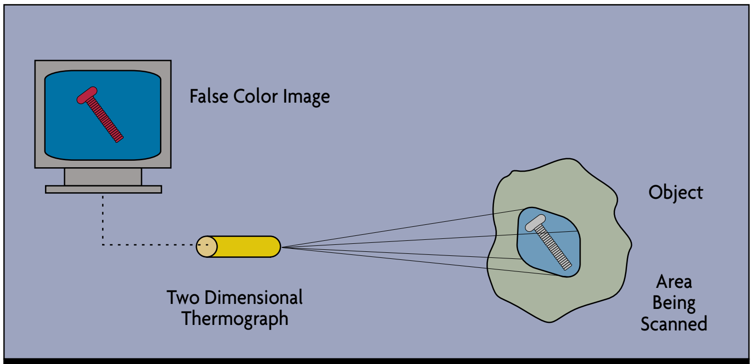


Figure 6-3: 2-D Thermographic Camera

a predetermined route and visiting plant assets in a specific sequence. This makes data collection as efficient as possible. At each asset, the technician collects data from discrete sensors while working from a check list so as not to miss a reading. In the case of thermography, the data consists of one or more images of the relevant machine parts. A bare bones infrared camera is nothing more than a data collector. Raw thermal data is of little value; it is what one does with the data that makes the difference.

After the thermographic data collection is complete, the technician or the data analyst evaluates the images for evidence of thermal anomalies that indicates a need for either scheduled or immediate repair. If maintenance work is warranted, the analyst prepares a report both to justify to others the need to spend money for repairs and to retain as part of the permanent records for the given plant asset.

Framing the Image

A certain level of skill and experience aided by common sense is a prime requisite in gathering and analyzing thermographic data. The technician using the imager in the field must be aware of reflections of irrelevant heat sources that appear to be coming from the object being scanned. Physically moving the imager to the left or right could make a dramatic difference in the apparent temperature of the object. The difference is caused by the reflections of shop floor lighting fixtures, sunlight through windows, and other extraneous sources.

As with taking snapshots with a single lens reflex camera, framing the scene is somewhat of an art. If the object is in the path of the heated or cooled air issuing from an HVAC system, the readings will be skewed. It may make more sense to return after sundown or to shut down the HVAC system to gather meaningful data. Analysts need common sense, as well. Modern cameras offer resolutions of a fraction of a degree.

Data Analysis Tools

Some thermal imagers work in conjunction with on-board microprocessors and specialized software that give the user the ability to quickly prepare diagnostic reports. In fact, downloading the field data to a desktop PC frees the technician to continue gathering data while the analyst prepares a report. But, report preparation is not the only enhancement to standard infrared picture.

Some thermal imagers simplify work for the user by making it possible to annotate thermal images with voice messages stored digitally with the digital image itself. Some units automate the process of setting the controls to permit the camera to capture the best, most information-rich thermal image as long as the view is in clear focus.

Watching a part "age" may be of great value to the plant maintenance department in predicting the expected failure date for a machine component. Being able to trend thermal data as a function of time is one way to watch the aging process. The software package that processes the thermal data from the camera can produce a graph of the time-series temperature data corresponding to the same point in the infrared image of the plant asset. The analyst simply moves a spot meter to the part of the image to be trended and the temperature data for that spot links to a spreadsheet cell.

These enhancements to the basic thermographic technology continue to make the IR imagers easier to use. With a few hours of training, even a novice can generate excellent thermal scans that capture all the thermal information present in a given scene.

Industrial Applications

Electrical wiring involves many discrete physical connections between cables and various connectors, and between connectors and mounting studs on equipment. The hallmark of a high-quality electrical connection is very low electrical resistance

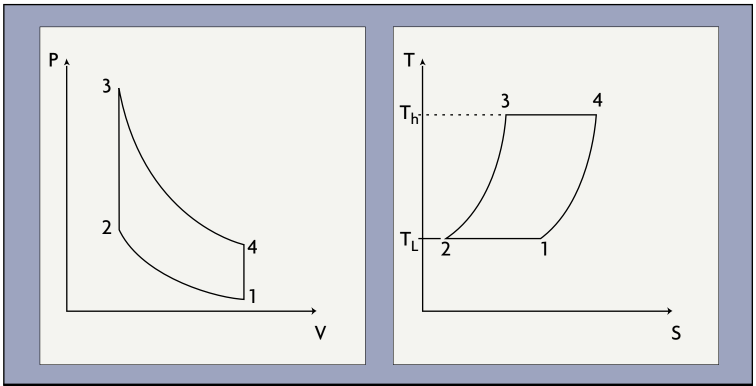
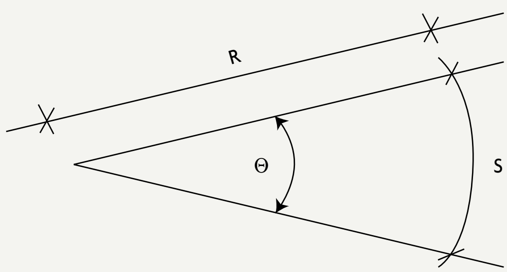


Figure 6-4: The Stirling Cycle



$S = R\Theta k$
S = Spot Diameter
R = Distance to Target
Θ = Imaging Spot Resolution [=] Milliradians
k = Constant Based on Units of Measure for S & R

k Values		Distance Units: Feet	Distance Units: Meters
Spot Size Units	Millimeters	0.305	1.000
	Inches	0.012	0.039

Figure 6-5: Spatial Resolution of a Thermographic Camera

between the items joined by the connection. Continued electrical efficiency depends on this low contact resistance.

Passing a current through an electrical resistor of any sort dissipates some of the electrical power. The dissipated power manifests itself as heat. If the quality of the connection degrades, it becomes, in effect, an energy dissipating device as its electrical resistance increases. With increased resistance, the connector or joint exhibits a phenomenon called ohmic heating. Electricians and maintenance technicians use the thermographic camera to locate these hot spots in electrical panels and wiring. The heated electrical components appear as bright spots on a thermogram of the electrical panel.

Three-phase electrical equipment connects to the power supply through three wires. The current through each wire of the circuit should be equal in magnitude. However, it is possible to have an unbalance in the phases. In this case, the current in one of the phases differs significantly from the others. Consequently, there exists a temperature difference among the three connections. Thermographic cameras can illustrate this imbalance quite easily and dramatically. Consider, for a moment, the ease with which a thermographer can inspect overhead electrical connections or pole-mounted transformers from a remote, safe place on the ground.

Thermography also finds use in inspecting the building envelope. It can locate sections of wall that have insufficient insulation. It can also spot differences in temperatures that indicate air leaks around window and door frames. Thermal imaging is useful for inspecting roofs as well.

If a defect in the outermost roof membrane admits rain water that gets trapped between the layers making up the roof, the thermal conductivity of the waterlogged section of roof is greater than that of the surrounding areas. Because the thermal conductivity differs, so does the temperature of the outer roof membrane. An infrared camera can easily detect such roof problems. A thermal scan of the roof and a can of spray paint is all that is needed to identify possible roof defects for a roofing contractor to repair.

Because thermography is a non-contact measurement method, it makes possible the inspection of mechanical systems and components in real time without shutting down the underlying production line.

Energy constitutes a major cost in most manufacturing plants. Every wasted BTU represents a drain on plant profitability. Thermography lends itself to eliminating the energy loss related to excessive steam consumption and defective steam traps. If steam is leaking through a steam trap, it heats the downstream condensate return piping. The heated section of piping is clearly visible to an infrared imager.

Heat loss to the surrounding environment is a function of temperature of the inside temperature. The heat loss increases nonlinearly with increased temperature because radiant losses can easily exceed convective and conductive losses at higher temperatures. For example, the refractory block installed inside of a kiln, boiler, or furnace is intended to minimize heat loss to the environment. Thermography can quickly locate any refractory defects. Another application for the technology is a blast furnace, with its massive amount of refractory.

The location of the blockage in a plugged or frozen product transfer line can sometimes be detected with thermography. If the level indicator on a storage tank fails, thermography can reveal the level of the inventory in the tank.

Thermography finds further use in the inspection of concrete bridge decks and other paved surfaces. The defects in question are voids and delamination in and among the various layers of paving materials. The air or water contained within the interlaminar spaces of the pavement slab affects its overall thermal conductivity. The IR imager can detect these defects.

Painted surfaces become multilayer composites when a bridge or storage tank has been repainted numerous times during its service life. Here, too, the possibility of hidden rust, blistering, cracking, and other delamination defects between adjacent paint layers make objective visual inspection difficult. A technique called transient thermography returns objectivity to the evaluation of a potentially costly repainting project.

Transient thermography entails using a pulse of thermal energy, supplied by heat lamps, hot air blowers, engine exhaust, or some similar source of energy, to heat the surface from behind for a short period of time. Because the imager detects temperature differentials of less than a degree, voids and delaminations become readily apparent.

Forestry departments use thermography to monitor the scope and range of forest fires to most efficiently deploy the valuable, limited, urgently needed resources of manpower and fire-retardant chemicals.

Corporate research and development rely on radiometric thermography, as well. Auto makers use the technology to optimize the performance of windshield defrosting systems and rear window defoggers. Semiconductor manufacturers use it to analyze operational failures in computer chips.

Enter the Microprocessor

Microprocessors and the software behind thermography units are important to the versatility of the technology. Digital control and high-speed communication links give thermographic devices the interconnectivity and signal processing expected in a digital manufacturing environment. For example, the linescanner output can be subdivided into several segments or zones, each corresponding to a portion of the width of the moving web. Each of these zones can provide individual 4-20 mA control and alarm signals to the process machinery.

Because the thermal data is digitized, it is easy to store the optimum thermograph for use as a standard of comparison. This standard thermal image—the golden image— is used to simplify process setup, a feature especially valuable when changing products in the processing line.

Contemporary thermographic units use 12-bit dynamic range architecture. This is the practical minimum if radiometry is to capture all the thermal information that the scene contains. It allows the analyst to position a set of crosshairs on a single pixel and determine the precise temperature that it represents.

The microprocessor also makes interpreting the thermogram easier. The analyst can spread the color palette across the full range of temperatures represented by the thermogram. For instance, when inspecting a roof in July, the temperature of every point in the scene is high and the difference in temperature between sound areas and defects is relative small, perhaps 20 degrees. On the other hand, production process may well mean that parts of the scene are 250 degrees (or more) warmer than the background objects. In either case, the analyst can spread 256 colors across the 20-degree and the 250-degree range in the scene to generate a usable picture. T

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IR Thermometer Calibration

Because of normal variations in the properties of materials used to construct radiation temperature sensors, new instruments must be individually calibrated in order to achieve even moderate levels of accuracy. Initial calibration is likely to be performed by the sensor manufacturer, but periodic recalibration—in-house or by a third-party laboratory or the original manufacturer—is necessary if any but the most qualitative measurements are expected.

Working much like a hot plate, this infrared calibration source uses a high emissivity, specially textured surface to provide a convenient temperature reference.

The ongoing accuracy of a non-contact temperature sensor will depend on the means by which the calibration is performed, how frequently it is recalibrated, as well as the drift rate of the overall system. Ensuring the absolute accuracy of non-contact temperature measurement devices is more difficult than with most direct contacting devices, such as thermocouples and resistance temperature detectors (RTDs). Limiting the absolute accuracy to 1% is difficult; even in the most sophisticated set-ups, better than 0.1% accuracy is seldom achieved. This arises, in part, from the difficulty in accurately determining the emissivity of real bodies. Repeatability or reproducibility is, however, more readily achievable than absolute accuracy, so don't pay more if consistency will do.

If absolute accuracy is a concern, then traceability to standards such as those maintained by the National Institute of Standards & Technology (NIST) will also be important. Traceability, through working to secondary to primary standards is central to the quality standards compliance such as those defined by the ISO 9000 quality standard.

Why Calibrate?

There are generally three methods of calibrating industrial radiation thermometers. One method is to use a commercial blackbody simulator, an isothermally heated cavity with a relatively small aperture through which the radiation thermometer is sighted (Figure 7-1). As explained in the earlier chapter on "Theoretical Development," this type of configuration approaches blackbody performance and its emissivity approaches unity. A standard thermocouple or resistance temperature detector (RTD) inside the cavity is used as the temperature reference. At higher temperatures, calibrated tungsten filament lamps are commonly used as references. A final alternative is to used a reference pyrometer whose calibration is known to be accurate, adjusting the output of the instrument being calibrated until it matches.

In any case, the radiation source must completely fill the instrument's field of view in order to check the

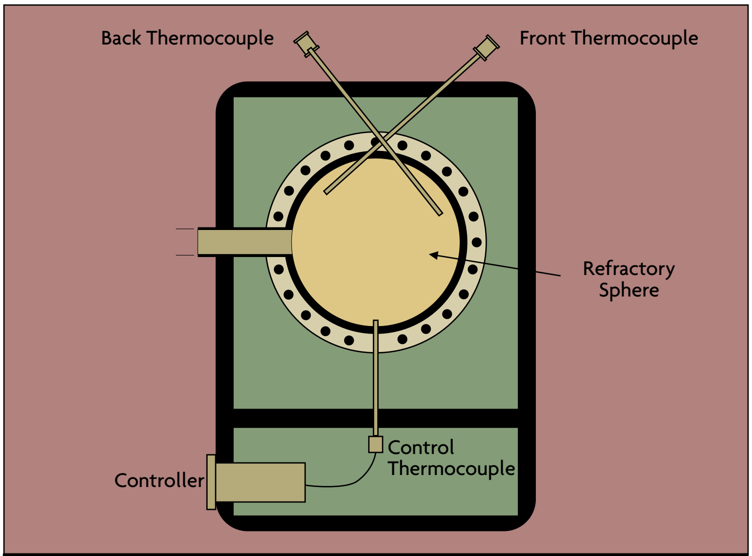

Figure 7-1: A Spherical Blackbody Cavity

calibration output. If the field of view is not filled, the thermometer will read low. In some instruments, calibration against a blackbody reference standard may be internal—a chopper is used to alternate between exposing the detector to the blackbody source and the surface of interest. Effectively, this provides continuous recalibration and helps to eliminate errors due to drift.

A handheld IR thermometer is calibrated against a commercial blackbody source—the internal cavity is designed to closely approach a blackbody's unity emissivity.

Blackbody Cavities

Because calibration of a non-contact temperature sensor requires a source of blackbody radiation with a precise means of controlling and measuring the temperature of the source, the interior surface of a heated cavity constitutes a convenient form, since the intensity of radiation from it is essentially independent of the material and its surface condition.

In order for a blackbody cavity to work appropriately, the cavity must be isothermal; its emissivity must be known or sufficiently close to unity; and the standard reference thermocouple must be the same temperature as the cavity. Essentially, the blackbody calibration reference consists of a heated enclosure with a small aperture through which the interior surface can be viewed (Figure 7-1). In general, the larger the enclosure relative to the aperture, the more nearly unity emissivity is approached (Figure 7-2). Although the spherical cavity is the most commonly referenced shape, carefully proportioned cone- or wedge-shaped cavities also can approach unity emissivity.

In order to provide isothermal surroundings for the cavity, the following materials commonly are used:

- Stirred water bath for 30-100°C (86-212°F) temperature ranges;
- Aluminum core for 50-400°C (122-752°F) temperature ranges; and
- Stainless steel core for 350-1000°C (662-1832°F) temperature ranges.

And while blackbody cavities have their appeal, they also have some disadvantages. Some portable, battery-operated units can be used at low temperatures (less than 100°C), but blackbody cavities are, for the most part, relatively cumbersome and expensive. They also can take a long time to reach thermal equilibrium (30 minutes or more), slowing the calibration procedure significantly if a series of measurements is to be made.

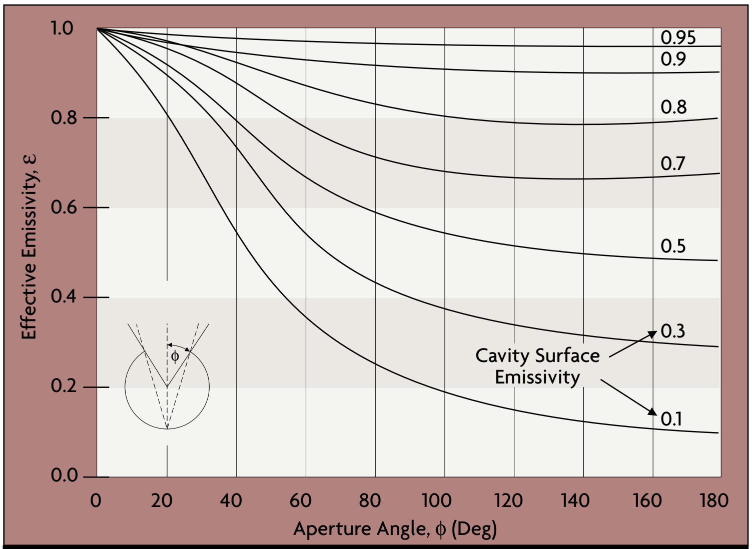

Figure 7-2: Effective Emissivity of Spherical Cavities

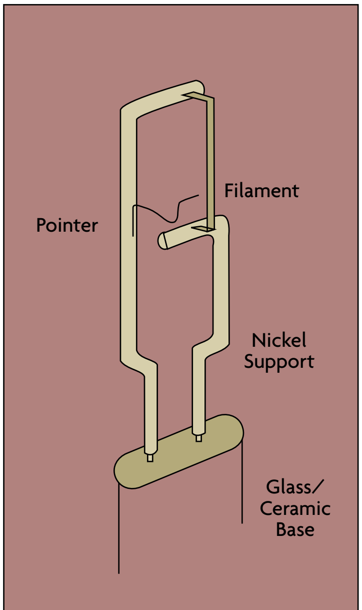

Figure 7-3: Typical Tungsten Lamp Filament

Tungsten Filaments

As a working alternative to blackbody cavities, tungsten ribbon lamps, or tungsten strip lamps, are commonly used as standard sources (Figure 7-3). Tungsten strip lamps are highly reproducible sources of radiant energy and can be accurately calibrated in the 800°C to 2300°C range. They yield instantaneous and accurate adjustment and can be used at higher temperatures than those readily obtainable with most cavities.

Lamps, however, must be calibrated in turn against a blackbody standard; the user typically is provided with the relationship between electric current to the filament and its temperature. Emissivity varies with temperature and with wavelength, but material is well understood enough to convert apparent temperatures to actual.

Just as a blackbody cavity includes a NIST-traceable reference thermocouple, instrument calibration against a ribbon lamp also can be traced to NIST standards. In a primary calibration, done mostly by NIST itself, filament current is used to balance standard lamp brightness against the goldpoint temperature in a blackbody furnace, in accordance with the ITS-90. Typical uncertainties range from ±4°C at the gold point to ± 40°C at 4000°C.

In secondary standard calibration, the output of a primary pyrometer, i.e., one calibrated at NIST, is compared with the output of a secondary pyrometer when sighted alternately on a tungsten strip lamp. Many systematic errors cancel out in this procedure and make it more practical for routine calibration. Ⓣ

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Products & Applications

While many of the earlier chapters of this volume have explored the physics and technology behind non-contact temperature measurement, now it's time to delve into the wide array of products that are available to take advantage of radiation phenomena—and how they're applied to industrial use.

Non-contact temperature sensors allow engineers to obtain accurate temperature measurements in applications where it is impossible or very difficult to use any other kind of sensor. In some cases, this is because the application itself literally destroys a contact-type sensor, such as when using a thermocouple or resistance temperature detector to measure molten metal. If the electrical interference is intense, such as in induction heating, the electromagnetic field surrounding the object will cause inaccurate results in conventional sensors. A remote infrared sensor is immune to both problems.

For maintenance, no other sensor is able to provide long-distance, non-contact temperature measurements needed to find hot spots or trouble areas in distillation columns, vessels, insulation, pipes, motors or transformers. As a maintenance and troubleshooting tool, it's difficult to beat a hand-held radiation thermometer.

Although non-contact temperature sensors vary widely in price, they include the same basic components: collecting optics, lens, spectral filter and detector. For more detailed technical information on each sensor type, see the previous chapters.

Alternative Configurations

The user can select among non-contact temperature sensors that operate over just about any desired wavelength range, both wide and narrow. Radiation thermometer sensitivity varies inversely proportionally with wavelength. Therefore, an instrument operating at 5 microns only has one-fifth the sensitivity of an instrument operating at 1 micron. This also means that optical noise and uncertainties in emissivity will result in measurement errors five times greater in the long wavelength instrument.

Radiation thermometer optics are usually the fixed focus type, although designs with through-the-lens focusing are available for measuring over longer distances. Fixed focus devices can also be used to measure at long distances if the target area is smaller than the lens diameter in the optical system.

Non-contact temperature sensors range from relatively inexpensive infrared thermocouples, priced from about $99, to sophisticated, comput-

Table 8-1: Strengths and Weaknesses of Non-Contact Temperature Sensors

INSTRUMENT TYPE	STRENGTHS	WEAKNESSES
IR Thermocouple	Inexpensive (from $99) Self-powered No measurement drift Plugs into standard thermocouple display and control devices Reaches into inaccessible areas Intrinsically safe	Nonlinear output Susceptible to EMI
Low-End IR Pyrometer/ Thermometer	Portable and convenient Inexpensive (from $235) Excellent maintenance tool	Maximum probe cable length of 1 m limits use
High-End IR Thermometer	Can focus on any target at almost any distance Portable or fixed-place operation Camera-like operation (point and shoot) Low to medium cost (from $350)	Measures only a fixed spot on target Accuracy affected by smoke, dust, etc. in line of sight Affected by EMI
Fiber Optic	Works in hostile, high-temperature, vacuum or inaccessible locations Can bypass opaque barriers to reach target Unaffected by EMI	Fairly expensive ($1600-$2600) Fixed Focus
Two-Color	Sees through smoke, dust and other contaminants in line of sight Independent of target emissivity	Fairly expensive (from $3600 for sensor, and $5000 for display/controller)
Linescanner	Only sensor that makes full-width temperature measurements across product Measures continuously as product passes by Computer can produce thermographic images of entire product and its temperature profile	Very expensive (from $10,000 for sensor alone, $50,000 for complete system)

er-based $50,000 linescanners. In between is a wide variety of hand-held and permanently mounted measuring systems that meet just about any temperature monitoring need imaginable.

Infrared Thermocouples

An infrared thermocouple is an unpowered, low-cost sensor that measures surface temperature of materials without contact. It can be directly installed on conventional thermocouple controllers, transmitters and digital readout devices as if it were a replacement thermocouple. An infrared thermocouple can be installed in a fixed, permanent location, or used with a hand-held probe.

Because it is self-powered, it relies on the incoming infrared radiation to produce a signal via thermoelectric effects. Therefore, its output follows the rules of radiation thermal physics, and is subject to nonlinearities. But over a given range of temperatures, the output is sufficiently linear that the signal can be interchanged with a conventional thermocouple.

Although each infrared thermocouple is designed to operate in a specific region, it can be used outside that region by calibrating the readout device accordingly.

Radiation Thermometers/Pyrometers

Radiation thermometers, or pyrometers, as they are sometimes called come in a variety of configurations. One option is a handheld display/control unit, plus an attached probe. The operator points the probe at the object being measured—sometimes getting within a fraction of an inch of the surface—and reads the temperature on the digital display. These devices are ideal for making point temperature measurements on circuit boards, bearings, motors, steam traps or any other device that can be reached with the probe. The inexpensive devices are self-contained and run off battery power.

Typical fiber optic probe, transmitter, and bench top display.

Other radiation thermometers are hand-held or mounted devices that include a lens similar to a 35mm camera. They can be focused on any close or distant object, and will take an average temperature measurement of the "spot" on the target that fits into its field of view.

Handheld radiation thermometers are widely used for maintenance and troubleshooting, because a technician can carry one around easily, focus it on any object in the plant, and take instant temperature readings of anything from molten metals to frozen foods.

When mounted in a fixed position, radiation thermometers are often used to monitor the manufacturing of glass, textiles, thin-film plastic and similar products, or processes such as tempering, annealing, sealing, bending and laminating.

Fiber Optics Extensions

When the object to be measured is not in the line of sight of a radiation thermometer, a fiber optic sensor can be used. The sensor includes a tip, lens, fiber optic cable, and a remote monitor unit mounted up to 30 ft away. The sensor can be placed in high energy fields, ambient temperatures up to 800°F, vacuum, or in otherwise inaccessible locations inside closed areas.

Two-Color Systems

For use in applications where the target may be obscured by dust, smoke or similar contaminants, or changing emissions as in "pouring metals," a two-color or ratio radiation thermometer is ideal. It measures temperature independently of emissivity. Systems are available with fiber optic sensors, or can be based on a fixed or hand-held configurations.

Linescanners

A linescanner provides a "picture" of the surface temperatures across a moving product, such as metal slabs, glass, textiles, coiled metal or plastics. It includes a lens, a rotating mir-

Hand-held IR thermometers include such options as laser sights.

ror that scans across the lens' field of view, a detector that takes readings as the mirror rotates, and a computer system to process the data.

As the mirror rotates, the line scanner takes multiple measurements across the entire surface, obtaining a full-width temperature profile of the product. As the product moves forward under the sensor, successive scans provide a profile of the entire product, from edge to edge and from beginning to end.

The computer converts the profile into a thermographic image of the product, using various colors to represent temperatures, or it can produce a "map" of the product. The 50 or so measurement points across the width can be arranged in zones, averaged, and used to control upstream devices, such as webs, cooling systems, injectors or coating systems.

Linescanners can be extremely expensive, but they offer one of the only solutions for obtaining a complete temperature profile or image of a moving product.

Portable vs. Mounted

Non-contact temperature measurement devices also can be classified as portable or permanently mounted. Fixed mount thermometers are generally installed in a location to continuously monitor a process. They often operate on AC line power, and are aimed at a single point. Measured data can be viewed on a local or remote display, and an output signal (analog or digital) can be provided for use elsewhere in the control loop. Fixed mount systems generally consist of a housing containing the optics system and detector, connected by cable to a remote mounted electronics/display unit. In some loop-powered designs, all the thermometer components and electronics are contained in a single housing; the same two wires used to power the thermometer also carry the 4 to 20 mA output signal.

Battery powered, hand-held "pistol" radiation thermometers typically have the same features as permanently mounted devices, but without the output signal capability. Portable units are typically used in maintenance, diagnostics, quality control, and spot measurements of critical processes.

Portable devices include pyrometers, thermometers and two-color systems. Their only practical application limit is the same as a human operator; i.e., the sensors will function in any ambient temperature or environmental condition where a human can work, typically 32-120°F (0-50°C).

At temperature extremes, where an operator wears protective clothing, it may be wise to similarly protect the instrument. In shirt-sleeve manufacturing or process control applications, hand-held instruments can be used without worrying about the temperature and humidity, but care should be taken to avoid sources of high electrical noise. Induction furnaces, motor starters, large relays and similar devices that generate EMI can affect the readings of a portable sensor.

Portable non-contact sensors are widely used for maintenance and troubleshooting. Applications vary from up-close testing of printed circuit boards, motors, bearings, steam traps and injection molding machines, to checking temperatures

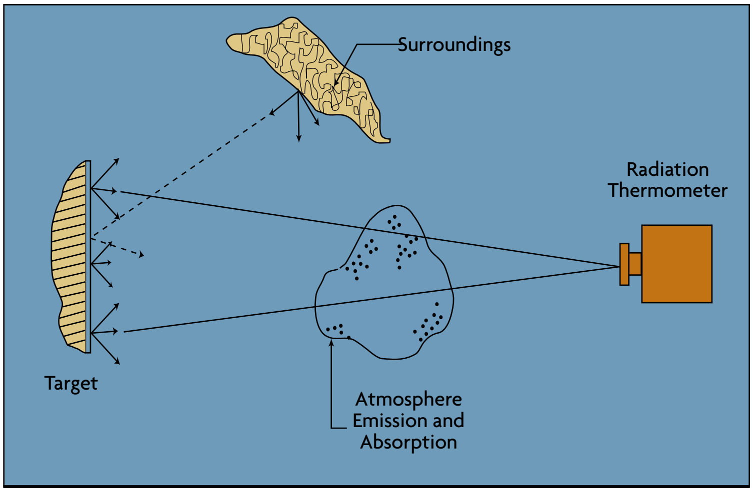

Figure 8-1: Ambient Effects on IR Thermometer Accuracy

remotely in building insulation, piping, electrical panels, transformers, furnace tubes and manufacturing and process control plants.

Because an infrared device measures temperature in a "spot" defined by its field of view, proper aiming can become critical. Low-end pyrometers have optional LED aiming beams, and higher end thermometers have optional laser pointing devices to help properly position the sensor.

Permanently mounted devices are generally installed on a manufacturing or process control line, and output their temperature signals to a control or data acquisition system. Radiation thermometers, two-color sensors, fiber optics, infrared thermocouples, and linescanners can all be permanently mounted.

In a permanent installation, an instrument can be very carefully aimed at the target, adjusted for the exact emissivity, tuned for response time and span, connected to a remote device such as an indicator, controller, recorder or computer, and protected from the environment. Once installed and checked out, such an instrument can run indefinitely, requiring only periodic maintenance to clean its lenses.

Instruments designed for permanent installation are generally more rugged than lab or portable instruments, and have completely different outputs. In general, systems that operate near a process are ruggedized, have NEMA and ISO industrial-rated enclosures, and output standard process control signals such as 4-20 mA dc, thermocouple mV signals, 0-5 Vdc, or serial RS232C.

For very hot or dirty environments, instruments can be equipped with water or thermoelectric cooling to keep the electronics cool, and nitrogen or shop air purging systems to keep lenses clean.

Application Guidelines

For first level sorting, consider speed of response, target size (field of view), and target temperature. Once the list of possible candidates for the application has narrowed, consider things like band pass and sensitivity of the detector, transmission quality of the optical system and transmission quality of any windows or atmosphere in the sighting path, emissivity of the target, ambient conditions, and the process dynamics (steady state variations or step changes). These are shown graphically in Figure 8-1.

If 90% response to a step change in temperature is required in less than a few seconds, pyrometers with thermal detectors may not be suitable, unless you use thermopiles. A pyrometer with a photon detector may be a better choice.

Thermometers with targets of 0.3 to 1 inch diameter with a focal distance of 1.5 to 3 feet from the lens are common. If a target size in this range is needed to sight on a large target through a small opening in a furnace, a pyrometer in which target size increases rapidly with distance beyond the focal plane may be fit the bill. Otherwise, a thermometer with more sophisticated optics and signal conditioning may be required.

If the temperature to be measured is below 750°F (400°C) a more sophisticated pyrometer with optical chopping can improve performance.

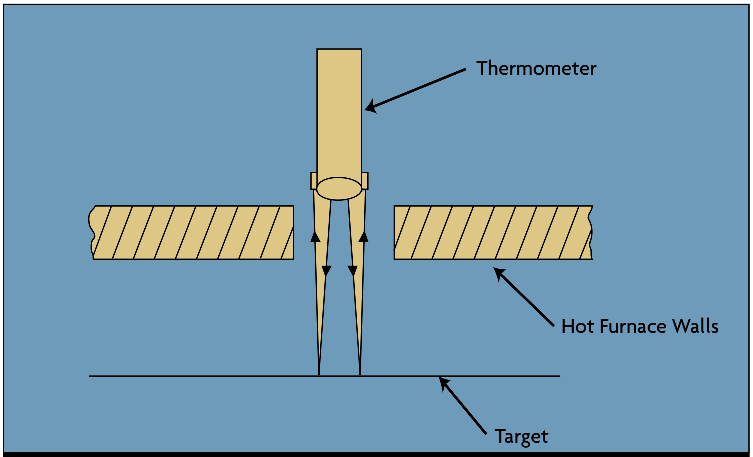

Figure 8-2: Sighting on a Specular Surface

If the surroundings between the thermometer and the target are not uniform, or if a hot object is present, it is desirable to shield the field of view of the instrument so that these phenomenon have minimal effect on the measurement.

Any radiation absorbed or generated by gases or particles in the sighting path will affect measured target temperature. The influence of absorbing media (such as water vapor) can be minimized by proper selection of the wavelengths at which the thermometer will respond. For example, a pyrometer with a silicon detector operates outside the absorption bands of water vapor and the error is nil. The influence of hot particles can be eliminated by ensuring they do not enter the sighting path, or by peak or valley picking, if they are transiently present. A open ended sighting tube, purged with a low temperature gas can provide a sighting path free of interfering particles.

Thermometers selected to measure transparent targets, such as glass or plastic films, must operate at a wavelength where the transmission of these materials is low so hot objects behind the target do not interfere with the measurement. For example, most glass is opaque at wavelengths above 5 microns if it is 3 mm or thicker. The emittance of glass decreases at higher wavelengths above 8 microns because of its high reflection, so measurement at higher wavelengths is not as desirable. If the incorrect band is picked, the thermometer will sight through the glass and not read the surface temperature.

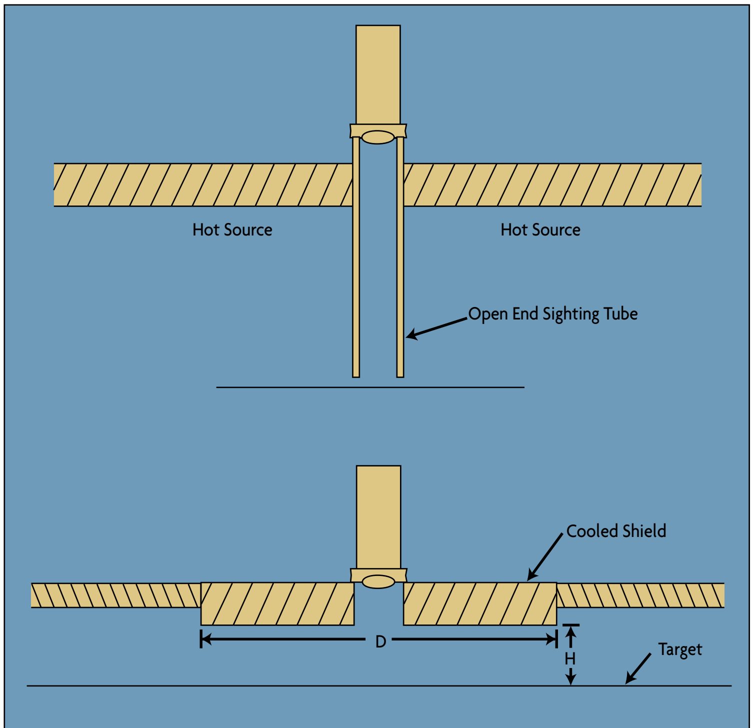

Figure 8-3: Use of Shielding and Cooling

Imagine, for example, two thermometers measuring the surface temperature of a lightbulb. One thermometer operates in the 8 to 14 micron range, and the other operates at 2 microns. The 8 to 14 micron device reads the surface temperature of the bulb as 90°C. The 2-micron device, sees through the surface of the glass, to the filament behind, and reads 494°C.

Other parameters to consider when selecting a non-contact temperature sensor include:

- *Target material*—The composition of a target determines its emissivity, or the amount of thermal energy it emits. A blackbody is a perfect emitter, rated 1.0 or 100%. Other materials are somewhat lower; their emissivity can be anywhere from 0.01 to 0.99, or 0-99%. Organic materials are very efficient, with emissivities of 0.95, while polished metals are inefficient, with emissivities of 20% or less. Tables only give the emissivity of an ideal surface, and cannot deal with corrosion, oxidation or surface roughness. In the real world, emissivity variations range from 2 to 100% per 100°F temperature change. When in doubt, obtain an appropriate instrument and measure the emissivity exactly.
- *Temperature range*—The emissivity and the range of expected temperatures of the target determine the wavelengths at which the target will emit efficiently. Choose a sensor that is sensitive at those wavelengths. Accuracy is listed as a percent of full scale or span, so the closer the temperature range to be measured can be specified, the closer sensor match, and the more accurate the final measurements.
- *Wavelength choice*—Manufacturers typically lists their products with a given temperature range and wavelength, with wavelengths listed in microns. Note that more than one wavelength can apply in any given application. For example, to measure glass, a wavelength of 3.43, 5.0 or 7.92 microns can be used, depending on the depth you want to measure, the presence of tungsten lamps, or to avoid reflections. Measuring plastic films presents the same problems. You may want to use a broad spectrum to capture most of the radiant emissions of the target, or a limited region to narrow the temperature range and increase accuracy. In many applications, various conditions and choices may exist. You may want to consult with your supplier.
- *Atmospheric interference*—What is present in the atmosphere between the sensor and the target? Most non-

contact temperature sensors require an environment that has no dust, smoke, flames, mist or other contaminants in the sensor's line of sight. If contaminants exist, it may be necessary to use a two-color sensor. If there is an obstructed line of sight, it may be necessary to use a fiber optic probe to go around the obstacles.

- *Operating Environment*—Into what kind of environment will the sensor itself be installed? If it is hazardous, hot, humid, corrosive or otherwise unfriendly, it will be necessary to protect the instrument. Lenses and cases are available to withstand corrosives; air purge systems can protect lenses from process materials; and various cooling systems are available to cool the lenses, optics and electronics.

If the surrounding temperature is the same as the target temperature, the indicated temperature from a radiation thermometer will be accurate. But if the target is hotter than the surroundings, it may be desirable to use a device with a high N* value to minimize the emissivity error and minimize radiation from the surroundings reflected into the thermometer. Two approaches can be used when the target is at a lower temperature than the surroundings. The first method, Figure 8-2, is possible if the target is fixed, flat, and reflects like a mirror. The thermometer is arranged so that it sights perpendicular to the target.

To measure the temperature of a target with a matte surface, you must shield the field of view of the thermometer so that energy from hot objects does not enter. One approach, shown in Figure 8-3, involves sighting the thermometer through an open ended sighting tube. The other approach is to use a cooling shield. The shield must be large enough so that D/H ratio is 2 to 4. This method can not be used for slowly moving or stationary targets. An uncooled shield can be used to block out radiation from a small, high temperature source that will not heat it significantly.

A closed end sight tube is an accessory that can be used to protect optics and provide a clear sight path for broadband thermometers. The one end of the tube reads the same temperature as the target (it may be touching the target or very close to it), while cooling can be used to protect the thermometer itself, at the other end of the tube, from high temperatures. A closed or open end sight tube can prevent attenuation of emitted radiation by water vapor, dust, smoke, steam and radiation absorptive gases in the environment.

Industrial applications invoke either surface temperature of objects in the open, or temperatures inside vessels, pipes and furnaces. The target may need to sight through a window in the latter case. The thermometer, if permanently installed, can be mounted to an adjacent pedestal, or attached to the vessel. Hardware is available from manufacturers to accomplish this. The thermometer housing may need to be protected from excessive heat via a cooling mechanism, and/or may require a continuous clean gas purge to prevent dirt accumulation. Hardware is optionally available for both needs.

The accessories needed for difficult applications, for example, to permanently install a radiation thermometer on the wall of a furnace, can easily escalate the cost of an infrared thermometer into the thousands of dollars, doubling the price of the standard instrument. In Figure 8-4, for example, the thermocouple

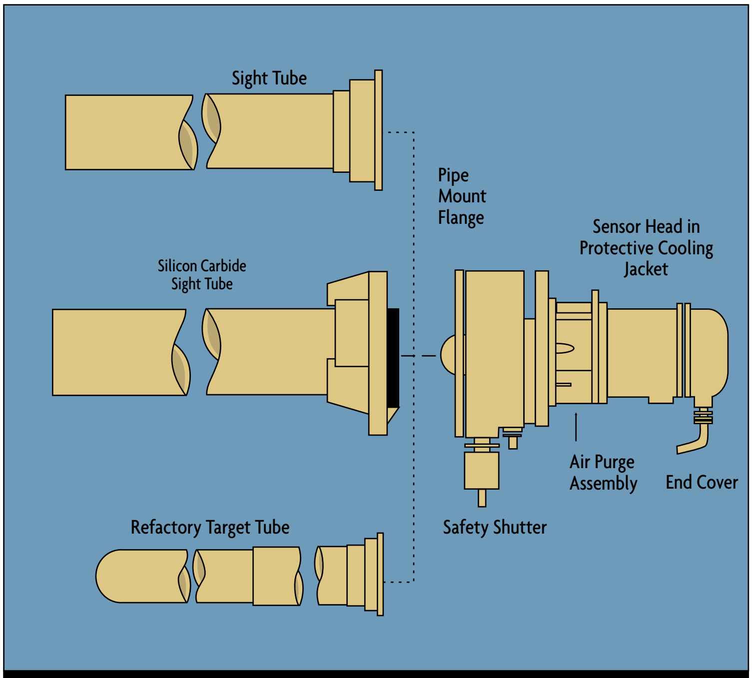

Figure 8-4: Accessories for Furnace-Wall Installation

*Refer to page 25

sensor head and its aiming tube are mounted inside a cooling jacket. The coolant flow required depends on the actual ambient conditions which exist. Also shown are an air purge assembly, and a safety shutter. The latter allows the furnace to be sealed whenever the radiation thermometer must be removed.

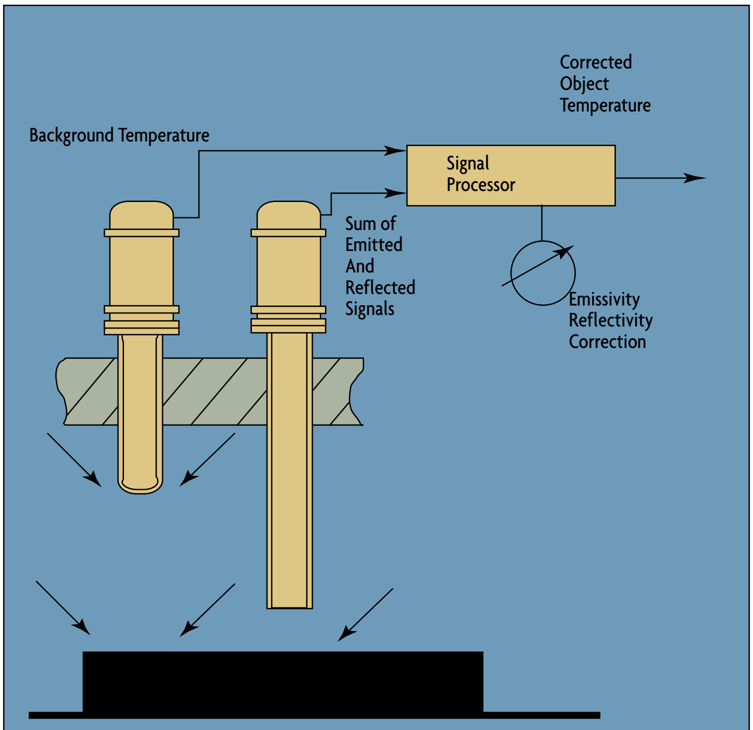

Figure 8-5: Compensation for Elevated Ambient Temperatures

If the target and the surroundings are not at the same temperature, additional sensors, as shown in Figure 8-5 need to be supplied. This configuration allows automatic compensation in the radiation thermometer electronics for the effects of the surroundings on the target temperature reading.

There is a lot to consider when selecting and installing a non-contact sensor to measure a critical process temperature. And to the unfamiliar, the task can seem mind boggling. How do I get emissivity data? Which wavelength(s) is best for my application? What options do I really need? .... and a thousand other questions easily come to mind. But help is available. For example, many manufacturers have open Internet sights that contain an abundance of helpful information to assist the first time user in getting started. (See list of resources, p. 68.) In addition, there are consultants, as well as the manufacturers themselves, who can supply all the assistance needed to get up and running quickly.

• Industrial Applications

In most cases, at least one of the sensors we've discussed can be used to measure temperature in any kind of application, from -50 to 6,500°F . The key is to identify the sensor that will do the best job. This can be a very simple or an extremely difficult choice. Perhaps some of the applications listed below will give you a few ideas on how to use a non-contact temperature sensor in your plant.

- *Airplane Checkout*—The sheer size and height of a widebody 747 aircraft makes it very difficult for technicians to check the operation of various devices, such as pitot tubes and heating tapes used to warm pipes, water and waste tanks in various parts of the aircraft. Before, a technician had to climb a 25-ft ladder and touch the surfaces to see if the devices were working properly.

Now, a radiation thermometer is used during final assembly to check the operation of various heating elements. The technician stands on the ground, and aims the thermometer at each pitot tube or heating element. Boeing reports saving 4-5 construction hours on each jet.

- *Asphalt*—Asphalt is very sensitive to temperature during preparation and application. Thermocouples normally used to measure asphalt temperature usually have severe breakage problems because of the abrasiveness of the material. Infrared thermocouples are an ideal replacement.

The sensor can be mounted so that it views the asphalt through a small window in the chute, or slightly above for viewing at a distance. In either case, the sensor should have an air purge to keep the lens clean from vapor or splashes. Plus, it can be connected to the control system as if it was a thermocouple.

- *Electrical System Maintenance*—Infrared scanning services are becoming widely available. Typically, a scanning service brings in a portable imaging processor and scanner twice a year to check a building's switchgear, circuit breakers, and other electrical systems. The service looks for hot spots and temperature differences.

Between visits, maintenance personnel can perform spot checks and verify repairs with an inexpensive radiation thermometer. Attaching a data logger lets a technician determine heating trends of switchgear during peak periods, and identify the parts of system that suffer the most when electrical consumption goes up.

- *Flame Cutting*—In flame cutting, before a computer cuts various shapes from steel plate, the steel surface has to be heated by a natural gas or propane flame. When a "puddle" of molten metal is detected by the operator, oxygen is injected into the gas stream. This blows the molten metal through the plate and the cutting cycle begins. If oxygen is injected prematurely, it makes a defective cut, leaving an objectionable rough and wide pit-like depression in the plate.

A fiber optic sensor can be mounted on the torch and aimed to look through the gas stream at the plate surface. It will detect the proper plate temperature for puddling, and inform the operator.

- *Glass*—An infrared thermometer is ideal for measuring the temperature of soda-lime-silica glass, predominantly used in making sheet, plate, and bottles. The biggest problem is that glass has relatively poor thermal conductivity, so temperature gradients exist at various depths. The three most commonly used wavelengths for measuring glass—3.43, 5.0, and 7.92 microns—each see a different distance into the glass. A sensor with 7.92 microns sees only the surface, while a 3.43 micron sensor can see up to 0.3 in. into the glass.

The trick is to select a thermometer which is not adversely influenced by thickness variations. Your best bet may be to send samples of glass products to the thermometer manufacturer, and let them advise you on what device to use.

During installation, select the aiming point so that the instrument doesn't see any hot objects behind the transparent glass, or any reflected radiation from hot objects in front of the glass. Aim the sensor at an angle that avoids reflections, or install an opaque shield to block the reflections at the source. If neither is possible, use either of the higher wavelength sensors, because they are not affected as much by reflections.

Be careful of applications where the glass is heated with high intensity, tungsten filament quartz

Table 8-2: Successful Radiation Thermometer Applications

	MOUNTED			PORTABLES		
	2	H	L	2	H	L
Cement Kilns Burning zones, preheaters	•	•		•	•	
Energy Conservation Insulation and heat flow studies, thermal mapping			•			•
Filaments Annealing, drawing, heat treating	•			•		
Food Baking, candy-chocolate processing, canning freezing, frying, mixing, packing, roasting			•			•
Furnaces flames, boiler tubes, catalytic crackers	•	•		•	•	
Glass Drawing, manufacturing/processing bulbs, containers, TV tubes, fibers	•	•	•	•	•	•
Maintenance Appliances, bearings, currentoverloads, drive shafts, insulation, power lines, thermal leakage detection			•			•
Metals (ferrous and nonferrous) annealing, billet extrusion, brazing, carbonizing, casting, forging, heat treating, inductive heating, rolling/strip mills, sintering, smelting	•	•		•	•	
Metals, Pouring	•					
Quality Control printed circuit boards, soldering, universal joints, welding, metrology	•	•	•	•	•	•
Paint Coating, ink drying, printing, photographic emulsions, web profiles			•			•
Paper Blow-molding, RIM, film extrusion, sheet thermoforming, casting			•			•
Plastic Blow-molding, RIM, film extrusion, sheet thermoforming, casting			•	•		•
Remote Sensing Clouds, earth surfaces, lakes, rivers, roads, volcanic surveys			•			•
Rubber Calendaring, casting, molding, profile extrusion, tires, latex gloves	•		•	•		•
Silicon Crystal growing, strand/fiber, wafer annealing, epitaxial deposition			•			•
Textile Curing, drying, fibers, spinning	•			•		
Vacuum Chambers Refining, processing, deposition						
2=2-color sensor H=High Temperature L=Low Temperature						

lamps. These generate radiation levels that interfere with thermometers operating below 4.7 microns. In this case, use a 7.92 micron sensor.

- *Glass Molds*—The temperature of the mold or plunger used to make glass containers is critical: if too hot, the container may exit the mold and not retain its shape; if too cool, it may not mold properly. Molds must be measured constantly to ensure that cooling is proceeding correctly.

An infrared thermometer can be used to take mold measurements. A few suggestions: Don't measure new molds. They are usually shiny and clean, so they are reflective and have low emissivity. As they get older, they get dull and non-reflective, and the emissivity becomes higher and more repeatable. Use a radiation thermometer with a short wavelength, such as 0.9 microns, or a two-color instrument.

- *Humidity*—An infrared thermocouple can be used to measure relative humidity in any situation where there is a convenient source of water and flowing air. Aim the device at a wet porous surface with ambient air blowing across. When air moves across a wet surface, water cools by evaporation until it reaches the wet-bulb temperature, and cooling stops. The sensor can be connected to a display that records the lowest temperature, which is the wet-bulb temperature, and can be used to calculate the relative humidity.

- *Immersion Thermowells*—Thermowells protrude into a high-pressure vessel, stack, pipe or reactor, allowing a temperature sensor to get "inside" while maintaining process integrity. An infrared thermocouple or fiber optic sensor can be positioned outside the thermowell looking in, rather than being mounted inside the thermowell. Conventional sensors subjected to constant high temperatures suffer metallurgical changes that affect stability and drift. But the non-contact sensors, because they are outside, do not suffer such problems. They also respond more quickly; essentially, the response time of a radiation sensor is the same as the thermowell. Also, since the sensor is outside, it will survive much longer in a very high temperature environment than a conventional sensor will.

To install a radiation thermometer in a thermowell, mount it so it is aimed directly into a hollow thermowell, and adjust its distance so that its "spot size" is the same diameter as the thermowell. This way, the sensor will monitor temperature at the thermowell tip. If the thermowell has a sight glass, select a sensor that can see through it.

- *Induction Heating*—Measuring the temperature of an induction heating process can be accomplished with infrared thermocouples, thermometers or fiber optic sensors.

An infrared thermocouple will operate in the very strong electrical field surrounding induction heaters. Make sure the sensor's shield wire is attached to a proper signal ground. The preferred method is to view the part between the coil turns or from the end. If there is excessive heating on the sensor, use a water cooling jacket (you can use the same water source used to cool the induction coil).

Fiber optic sensors should be mounted so the viewing end is placed close to the target. The tip of the fiber can be positioned between the induction coils. Replaceable ceramic tips can be used to minimize damage and adverse effects from the radio frequency field. If the fiber won't fit, use a lens system to monitor the surface from a distance. Fiber optic sensors are not normally affected by induction energy fields, but if the noise is excessively high, use a synchronous demodulation system. The demodulator converts the 400 Hz ac signal from the detector head to dc, which is more

Table 8-3: Typical Application Temperature Ranges

APPLICATION	TEMP. RANGES
General purpose for textile, printing, food, rubber, thick plastics, paints, laminating, maintenance	-50 to 1000°C -58 to 1832°F
Life sciences, biology, zoology, botany, veterinary medicine, heat loss and research	0 to 500°C 32 to 932°F
Thin film plastic, polyester, fluorocarbons, low temperature glass	50 to 600°C 122 to 1112°F
Glass and ceramic surfaces, tempering,annealing, sealing, bending and laminating	300 to 1500°C 572 to 2732°F
See-through clean combustion flames and hot gases. Furnace tubes	500 to 1500°C 932 to 2732°F
Medium to high temperature ferrous and non-ferrous metals. See-through glass	250 to 2000°C 482 to 3632°F
Hot and molten metals, foundries, hardening, forging, annealing, induction heating	600 to 3000°C 1112 to 5432°F

immune to noise.

- ***Plastic Film***—A film of plastic or polymer emits thermal radiation like any other material, but it presents unique measuring problems for any sensor, including a radiation thermometer. As with glass, when measuring film temperature, it's important to install it so the instrument doesn't see any hot objects behind the transparent film, or any reflected radiation from hot objects in front of the film.

For films of 1, 10 or 100 mil thicknesses, a wavelength of 3.43 or 7.92 microns will work for cellulose acetate, polyester (polyethylene terephthalate), fluoroplastic (FEP), polymide, polyurethane, polyvinyl chloride, acrylic, polycarbonate, polymide (nylon), polypropylene, polyethylene and polystyrene.

As with glass, be careful of applications where the film is heated with high intensity, tungsten filament quartz lamps. These generate radiation levels that interfere with thermometers operating below 4.7 microns. In this case, use a 7.92 micron sensor.

- ***Web Rollers***—Infrared sensors can be used to measure the temperature of rollers used in various web processes, even if they are chrome plated. Uncoated metal or chrome rollers are difficult for an IR sensor to see, because they have low emissivity and the sensor sees too many environmental reflections. In such a case, paint a black stripe on an unused portion of the roller and aim the device directly at the stripe.

Table 8-4: Application Wavelengths (Microns)

TYPICAL APPLICATIONS	0.65	0.9	1.0	0.7-1.08 and 1.68 2-color	1.55 and 1.68 2-color	1.65	2.0	3.43	3.9	5.0	7.9	8-14
Aluminum			•		•	•	•					
Asphalt										•	•	
Automotive		•	•	•	•	•	•	•			•	•
Appliances							•	•			•	•
Ammunition							•	•				•
Batteries							•					•
Cement	•	•	•	•			•		•		•	•
Construction Materials							•			•	•	
Fiberglass	•		•	•			•	•		•		•
Food Processing							•	•				•
Foundry	•	•	•	•			•					
Glass-Melting	•	•	•	•					•			
Glass-Flat									•	•		
Glass Bottles		•							•	•	•	
Heat Treating		•		•	•	•		•				
Induction Heating		•		•	•	•		•				
Kilns	•	•		•			•		•	•		•
Metalworking		•		•	•	•		•				
Mining				•								
Non-ferrous Metals			•		•	•		•				
Ovens		•	•	•	•	•	•	•	•	•	•	•
Paper							•			•	•	
Pharmaceutical											•	
Plastics							•			•	•	
Plastic Films								•			•	
Rubber							•			•	•	
Semiconductors		•	•	•	•		•		•	•		
Steel	•		•	•		•		•		•		
Textiles							•	•			•	•
Utilities				•							•	

SOURCE: IRCON

Dull metal rollers often provide reliable signals. Emissivity can shift if the rollers get covered with dirt, moisture or oil. If in doubt, simply paint a stripe. Non-metallic surfaced rollers provide a reliable signal no matter where the device is pointed.

Accessories, Features & Options

Radiation thermometers and thermocouples are available with a host of features to solve a wide range of application conditions. All infrared sensors are available in a wide range of wavelengths, temperature ranges and optical systems. Portable units almost always are available with carrying kits, and permanently mounted units are ruggedized. Listed below are other options, features and accessories that make these sensors more useful for certain types of applications.

Backlit LCD displays, integrally attached or remotely mounted from the thermometer, are available. Multiple variables can be viewed simultaneously on these displays. These data can include current temperature, minimum measured temperature (time based), maximum measured temperature (time based), average temperature measured (time based), and differential temperature (for example, between the target and the surroundings).

Microprocessor-based radiation thermometers have input options to allow data to be integrated into the measurement from other sensors or thermometers in the loop. For example, a separate thermocouple or RTD input to the thermometer can be used to compensate the measured target temperature for changing ambient temperature conditions.

Protection from high electromagnetic and radio frequency interference (EMI/RFI) is available if the thermometer must be installed in a difficult environments.

Most infrared thermometers can be supplied with an emissivity adjustment. In addition, some devices can be supplied with an adjustable field of view. This is accomplished by installing an iris in the optical system that can be opened or closed to provide wide or narrow angle field of views.

• Handheld IR Thermometers

Handheld instruments are generally completely self-contained, battery-powered units, with manual controls and adjustments and some form of digital readout. Units can be mounted on tripods. Other accessories include:

- ***Laser sights,*** which paint a visible spot on the target, making it easier to determine where the instrument is pointed. This option is available both integrally attached or detachable from the thermometer. Hand-held devices used for up-close spot temperature measurement (for example, to measure component temperature on printed circuit boards) can have audible focusing guides instead of light markers.
- ***Dataloggers***, for acquiring data from thermometers and recording it for future use;
- ***Digital printers***
- ***Electrical system scanners***, designed specifically for finding hot spots in electrical panels, switchgear, fuse panels, transformers, etc.
- ***Handheld***, shirt-pocket-size scanner for general surface temperature measurement.
- ***Outputs:*** RS232C serial and/or 1 mV/degree.

• Infrared Thermocouples

These self-powered devices generate a thermocouple signal output using radiated energy, but usually have no signal processing or display systems. An infrared thermocouple is a sensor only, but it does have a few options and accessories.

- Cooling jacket kits for air or water cooling;
- Handheld version for precise spot measurements;
- Close-focus model with up to 60:1 field of view;
- Periscope kit for right-angle measurements;
- Low-cost ($99) model with ABS plastic housing;
- Adjustable emissivity;
- Two-color pyrometry unit that uses short-wave and long-wave infrared thermocouples.

• Fiber Optic Sensors

Probes are available in lens cells of various sizes, with replaceable glass or quartz tips. Options include a ceramic/metal tip for high temperatures, a polymer bolt for extrusion applications, ejector pin probe for injection molding, and right angle prisms. Sensor probes also are available as optical rods up to 60 cm long.

Cables can be supplied in single, bifurcated or trifurcated fiber optic bundles, and enclosed in jackets made of flexible stainless steel (standard), ceramic, heavy duty wire braid for abrasion resistance, or Teflon for high radio frequency fields. Cables typically are up to 30 ft long.

• Indicators and Controllers

Display units and controllers are available in models ranging from a simple digital panel meter that displays the signal as a temperature in °F or °C, to complex multi-channel processors that perform signal conditioning, linearization, peak-picking, alarm monitoring, saving min/max values, signal averaging, data logging and a host of other signal processing and manipulation functions.

Mounted IR Thermometers

The same basic features, options and accessories are available for radiation thermometers, two-color systems, and line scanners. Ruggedized for use on the plant floor, all these devices have several accessories to help them survive in hostile environments.

- ***Air purge***—Attaches to front end of sensor housing and provides positive air pressure in front of the lens, preventing dust, smoke, moisture and other contamination from reaching lens. In two-color systems, it can attach to front of re-imaging lens.
- ***Air or water cooling jackets***—Available for warm (35°F above ambient) and hot (up to 400 °F) environments, cooling jackets keep sensor temperature at normal levels inside the enclosure.
- ***Peltier effect cooling***—Some line scanners have electronic cooling systems, using Peltier effect devices.
- ***Sighting accessories***, including sight tubes, laser pointing devices, and scopes.
- ***Onboard data logging functions*** are available, as well as options for thermal printers to retrieve stored data. Data can also be remotely transmitted digitally.
- ***Transmitters***—Ruggedized NEMA 4 housing with 4-20 mAdc and/or RS232C/RS485 outputs. T

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Information Resources

ORGANIZATIONS

NAME/ADDRESS	PHONE	WEB ADDRESS
Academy of Infrared Thermography 2955 Westsyde Road, Kamloops, BC, Canada, V2B 7E7	250/579-7677	www.netshop.net/~academy/
American Ceramic Society 65 Ceramic Drive, Columbus, OH 43214	614/268-8645	www.acers.org
American Institute of Chemical Engineers (AIChE) 345 East 47 Street, New York, NY 10017-2395	212/705-7338	www.aiche.org
American Society of Mechanical Engineers (ASME) 345 East 47th Street, New York, NY 10017	212/705-7722	www.asme.org
Electric Power Research Institute (EPRI) 3412 Hillview Avenue, Palo Alto, CA 94303	415/855-2000	www.epri.com
Fiber Optics Sensor System Facilities & Optical Fiber Drawing & Measuring Facilities, Dept. of the Navy 4555 Overlook Avenue, Washington, DC 20375	202/767-3744	
Infrared Information and Analysis Center (IRIA) Dept. of the Navy PO Box 8618, Ann Arbor, MI	313/994-1200	www.erim.org/IRIA
Infraspection Institute Shelburne, VT	802/985-2500	www.together.net/~werir
Institute of Electrical & Electronics Engineers (IEEE) 445 Hoes Lane, Piscataway, NJ 08855-1331	732/981-0060	www.ieee.org
ISA—The International Society for Measurement & Control 67 Alexander Drive, Research Triangle Park, NC 27709	919/549-8411	www.isa.org
International Society for Optical Engineers (SPIE) PO Box 10, Bellingham, WA 98277	206/676-3290	www.spie.org
Lawrence Berkeley National Laboratory, Infrared Thermography Laboratory Berkeley, CA 94720	510/486-6844 (Dariush Arasteh)	http://ucaccess.uirt.uci.edu/
National Institute of Standards & Technology Gaithersburg, MD 20899-0001.	301/975-3058	www.nist.gov

For the Latest Information on Non-Contact Temperature Instrumentation Products:

Omega Engineering, Inc.
One Omega Drive
P.O. Box 4047
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Phone: 800-82-66342 (800-TC-OMEGA℠)
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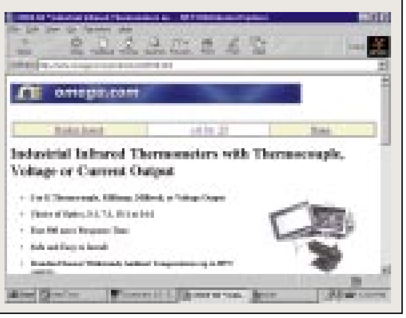
Website: www.omega.com



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Emissivity of Common Materials

Note: Because the emissivity of a given material will vary with temperature and surface finish, the value in these tables should be used only as a guide for relative or differential temperature measurements. The exact emissivity of a material should be determined when high accuracy is required.

METALS

MATERIAL	TEMP °F (°C)	ε-EMISSIVITY
A **Alloys**		
20-Ni, 24-CR, 55-FE, Oxidized	392 (200)	.90
20-Ni, 24-CR, 55-FE, Oxidized	932 (500)	.97
60-Ni, 12-CR, 28-FE, Oxidized	518 (270)	.89
60-Ni, 12-CR, 28-FE, Oxidized	1040 (560)	.82
80-Ni, 20-CR, Oxidized	212 (100)	.87
80-Ni, 20-CR, Oxidized	1112 (600)	.87
80-Ni, 20-CR, Oxidized	2372 (1300)	.89
Aluminum		
Unoxidized	77 (25)	.02
Unoxidized	212 (100)	.03
Unoxidized	932 (500)	.06
Oxidized	390 (199)	.11
Oxidized	1110 (599)	.19
Oxidized at 1110°F (599°C)	390 (199)	.11
Oxidized at 1110°F (599°C)	1110 (599)	.19
Heavily Oxidized	200 (93)	.20
Heavily Oxidized	940 (504)	.31
Highly Polished	212 (100)	.09
Roughly Polished	212 (100)	.18
Commercial Sheet	212 (100)	.09
Highly Polished Plate	440 (227)	.04
Highly Polished Plate	1070 (577)	.06
Bright Rolled Plate	338 (170)	.04
Bright Rolled Plate	932 (500)	.05
Alloy A3003, Oxidized	600 (316)	.40
Alloy A3003, Oxidized	900 (482)	.40
Alloy 1100-0	200-800 (93-427)	.05
Alloy 24ST	75 (24)	.09
Alloy 24ST, Polished	75 (24)	.09
Alloy 75ST	75 (24)	.11
Alloy 75ST, Polished	75 (24)	.08
B **Bismuth**		
Bright	176 (80)	.34
Unoxidized	77 (25)	.05
Unoxidized	212 (100)	.06
Brass		
73% Cu, 27% Zn, Polished	476 (247)	.03
73% Cu, 27% Zn, Polished	674 (357)	.03
62% Cu, 37% Zn, Polished	494 (257)	.03
62% Cu, 37% Zn, Polished	710 (377)	.04
83% Cu, 17% Zn, Polished	530 (277)	.03
Matte	68 (20)	.07
Burnished to Brown Color	68 (20)	.40
Cu-Zn, Brass Oxidized	392 (200)	.61
Cu-Zn, Brass Oxidized	752 (400)	.60
Cu-Zn, Brass Oxidized	1112 (600)	.61
Unoxidized	77 (25)	.04
Unoxidized	212 (100)	.04
Cadmium	77 (25)	.02 C
Carbon		
Lampblack	77 (25)	.95
Unoxidized	77 (25)	.81
Unoxidized	212 (100)	.81
Unoxidized	932 (500)	.79
Candle Soot	250 (121)	.95
Filament	500 (260)	.95
Graphitized	212 (100)	.76
Graphitized	572 (300)	.75
Graphitized	932 (500)	.71
Chromium	100 (38)	.08
Chromium	1000 (538)	.26
Chromium, Polished	302 (150)	.06
Cobalt, Unoxidized	932 (500)	.13
Cobalt, Unoxidized	1832 (1000)	.23
Columbium		
Unoxidized	1500 (816)	.19
Unoxidized	2000 (1093)	.24
Copper		
Cuprous Oxide	100 (38)	.87
Cuprous Oxide	500 (260)	.83
Cuprous Oxide	1000 (538)	.77
Black, Oxidized	100 (38)	.78
Etched	100 (38)	.09
Matte	100 (38)	.22
Roughly Polished	100 (38)	.07

	MATERIAL	TEMP °F (°C)	ε-EMISSIVITY
	Polished	100 (38)	.03
	Highly Polished	100 (38)	.02
	Rolled	100 (38)	.64
	Rough	100 (38)	.74
	Molten	1000 (538)	.15
	Molten	1970 (1077)	.16
	Molten	2230 (1221)	.13
	Nickel Plated	100-500 (38-260)	.37
D	**Dow Metal**	0.4-600 (-18-316)	.15
G	**Gold**		
	Enamel	212 (100)	.37
	Plate (.0001)		
	Plate on .0005 Silver	200-750 (93-399)	.11-.14
	Plate on .0005 Nickel	200-750 (93-399)	.07-.09
	Polished	100-500 (38-260)	.02
	Polished	1000-2000 (538-1093)	.03
H	**Haynes Alloy C**		
	Oxidized	600 2000 (316-1093)	.90-.96
	Haynes Alloy 25		
	Oxidized	600-2000 (316-1093)	.86-.89
	Haynes Alloy X		
	Oxidized	600-2000 (316-1093)	.85-.88
I	**Inconel**		
	Sheet	1000 (538)	.28
	Sheet	1200 (649)	.42
	Sheet	1400 (760)	.58
	X, Polished	75 (24)	.19
	B, Polished	75 (24)	.21
	Iron		
	Oxidized	212 (100)	.74
	Oxidized	930 (499)	.84
	Oxidized	2190 (1199)	.89
	Unoxidized	212 (100)	.05
	Red Rust	77 (25)	.70
	Rusted	77 (25)	.65
	Liquid	2700-3220 (1516-1771)	.42-.45
	Iron, Cast		
	Oxidized	390 (199)	.64
	Oxidized	1110 (599)	.78
	Unoxidized	212 (100)	.21
	Strong Oxidation	40 (104)	.95
	Strong Oxidation	482 (250)	.95
	Liquid	2795 (1535)	.29
	Iron, Wrought		

MATERIAL	TEMP °F (°C)	ε-EMISSIVITY	
Dull	77 (25)	.94	
Dull	660 (349)	.94	
Smooth	100 (38)	.35	
Polished	100 (38)	.28	
Lead			
Polished	100-500 (38-260)	.06-.08	
Rough	100 (38)	.43	
Oxidized	100 (38)	.43	
Oxidized at 1100°F	100 (38)	.63	
Gray Oxidized	100 (38)	.28	
Magnesium	100-500 (38-260)	.07-.13	M
Magnesium Oxide	1880-3140 (1027-1727)	.16-.20	
Mercury	32 (0)	.09	
Mercury	77 (25)	.10	
Mercury	100 (38)	.10	
Mercury	212 (100)	.12	
Molybdenum	100 (38)	.06	
Molybdenum	500 (260)	.08	
Molybdenum	1000 (538)	.11	
Molybdenum	2000 (1093	.18	
Oxidized at 1000°F	600 (316)	.80	
Oxidized at 1000°F	700 (371)	.84	
Oxidized at 1000°F	800 (427)	.84	
Oxidized at 1000°F	900 (482)	.83	
Oxidized at 1000°F	1000 (538)	.82	
Monel			
Monel, Ni-Cu	392 (200	.41	
Monel, Ni-Cu	752 (400)	.44	
Monel, Ni-Cu	1112 (600)	.46	
Oxidized	68 (20)	.43	
Oxidized at 1110°F	1110 (599)	.46	
Nickel			N
Polished	100 (38)	.05	
Oxidized	100-500 (38-260)	.31-.46	
Unoxidized	77 (25)	.05	
Unoxidized	212 (100)	.06	
Unoxidized	932 (500)	.12	
Unoxidized	1832 (1000)	.19	
Electrolytic	100 (38)	.04	
Electrolytic	500 (260)	.06	
Electrolytic	1000 (538)	.10	
Electrolytic	2000 (1093)	.16	
Nickel Oxide	1000-2000 (538-1093)	.59-.86	
Palladium Plate (.00005 on			P

MATERIAL	TEMP °F (°C)	ε-EMISSIVITY
.0005 silver)	200-750 (93-399)	.16-.17
Platinum	100 (38)	.05
Platinum	500 (260)	.05
Platinum	1000 (538)	.10
Platinum, Black	100 (38)	.93
Platinum, Black	500 (260)	.96
Platinum, Black	2000 (1093)	.97
Oxidized at 1100°F (593°C)	500 (260)	.07
Oxidized at 1100°F (593°C)	1000 (538)	.11
R **Rhodium Flash** (0.0002 on		
0.0005Ni)	200-700 (93-371)	.10-.18
S **Silver**		
Plate (0.0005 on Ni)	200-700 (93-371)	.06-.07
Polished	100 (38)	.01
Polished	500 (260)	.02
Polished	1000 (538)	.03
Polished	2000 (1093)	.03
Steel		
Cold Rolled	200 (93)	.75-.85
Ground Sheet	1720-2010 (938-1099)	.55-.61
Polished Sheet	100 (38)	.07
Polished Sheet	500 (260)	.10
Polished Sheet	1000 (538)	.14
Mild Steel, Polished	75 (24)	.10
Mild Steel, Smooth	75 (24)	.12
Mild Steel, Liquid	2910-3270 (1599-1793)	.28
Steel, Unoxidized	212 (100)	.08
Steel Oxidized	77 (25)	.80
Steel Alloys		
Type 301, Polished	75 (24)	.27
Type 301, Polished	450 (232)	.57
Type 301, Polished	1740 (949)	.55
Type 303, Oxidized	600-2000 (316-1093)	.74-.87
Type 310, Rolled	1500-2100 ((816-1149)	.56-.81
Type 316, Polished	75 (24)	.28
Type 316, Polished	450 (232)	.57
Type 316, Polished	1740 (949)	.66
Type 321	200-800 (93-427)	.27-.32
Type 321, Polished	300-1500 (149-815)	.18-.49
Type 321 w/BK Oxide	200-800 (93-427)	.66-.76
Type 347, Oxidized	600-2000 (316-1093)	.87-.91
Type 350	200-800 (93-427)	.18-.27
Type 350 Polished	300-1800 (149-982)	.11-.35

MATERIAL	TEMP °F (°C)	ε-EMISSIVITY
Type 446, Polished	300-1500 (149-815)	.15-.37
Type 17-7 PH	200-600 (93-316)	.44-.51
Type 17-7 PH Polished	300-1500 (149-815)	.09-.16
Type C1020, Oxidized	600-2000 (316-1093)	.87-.91
Type PH-15-7 MO	300-1200 (149-649)	.07-.19
Stellite, Polished	68 (20)	.18
Tantalum T		
Unoxidized	1340 (727)	.14
Unoxidized	2000 (1093)	.19
Unoxidized	3600 (1982)	.26
Unoxidized	5306 (2930)	.30
Tin		
Unoxidized	77 (25)	.04
Unoxidized	212 (100)	.05
Tinned Iron, Bright	76 (24)	.05
Tinned Iron, Bright	212 (100)	.08
Titanium		
Alloy C110M, Polished	300-1200 (149-649)	.08-.19
Alloy C110M, Oxidized		
at 1000°F (538°C)	200-800 (93-427)	.51-.61
Alloy Ti-95A, Oxidized		
at 1000°F (538°C)	200-800 (93-427)	.35-.48
Anodized onto SS	200-600 (93-316)	.96-.82
Tungsten		
Unoxidized	77 (25)	.02
Unoxidized	212 (100)	.03
Unoxidized	932 (500)	.07
Unoxidized	1832 (1000)	.15
Unoxidized	2732 (1500)	.23
Unoxidized	3632 (2000)	.28
Filament (Aged)	100 (38)	.03
Filament (Aged)	1000 (538)	.11
Filament (Aged)	5000 (2760)	.35
Uranium Oxide U	1880 (1027)	.79
Zinc Z		
Bright, Galvanized	100 (38)	.23
Commercial 99.1%	500 (260)	.05
Galvanized	100 (38)	.28
Oxidized	500-1000 (260-538)	.11
Polished	100 (38)	.02
Polished	500 (260)	.03
Polished	1000 (538)	.04
Polished	2000 (1093)	.06

NON-METALS

	MATERIAL	TEMP °F (°C)	ε-EMISSIVITY
A	**Adobe**	68 (20)	.90
	Asbestos		
	Board	100 (38)	.96
	Cement	32-392 (0-200)	.96
	Cement, Red	2500 (1371)	.67
	Cement, White	2500 (1371)	.65
	Cloth	199 (93)	.90
	Paper	100-700 (38-371)	.93
	Slate	68 (20)	.97
	Asphalt, pavement	100 (38)	.93
	Asphalt, tar paper	68 (20)	.93
B	**Basalt**	68 (20)	.72
	Brick		
	Red, rough	70 (21)	.93
	Gault Cream	2500-5000 (1371-2760)	.26-.30
	Fire Clay	2500 (1371)	.75
	Light Buff	1000 (538)	.80
	Lime Clay	2500 (1371	.43
	Fire Brick	1832 (1000)	.75-.80
	Magnesite, Refractory	1832 (1000)	.38
	Grey Brick	2012 (1100)	.75
	Silica, Glazed	2000 (1093)	.88
	Silica, Unglazed	2000 (1093)	.80
	Sandlime	2500-5000 (1371-2760)	.59-.63
C	**Carborundum**	1850 (1010)	.92
	Ceramic		
	Alumina on Inconel	800-2000 (427-1093)	.69-.45
	Earthenware, Glazed	70 (21)	.90
	Earthenware, Matte	70 (21)	.93
	Greens No. 5210-2C	200-750 (93-399)	.89-.82
	Coating No. C20A	200-750 (93-399)	.73-.67
	Porcelain	72 (22)	.92
	White Al_2O_3	200 (93)	.90
	Zirconia on Inconel	800-2000 (427-1093)	.62-.45
	Clay	68 (20)	.39
	Fired	158 (70)	.91
	Shale	68 (20)	.69
	Tiles, Light Red	2500-5000 (1371-2760)	.32-.34
	Tiles, Red	2500-5000 (1371-2760)	.40-.51
	Tiles, Dark Purple	2500-5000 (1371-2760)	.78
	Concrete		
	Rough	32-2000 (0-1093)	.94
	Tiles, Natural	2500-5000 (1371-2760)	.63-.62

MATERIAL	TEMP °F (°C)	ε-EMISSIVITY	
Brown	2500-5000 (1371-2760)	.87-.83	
Black	2500-5000 (1371-2760)	.94-.91	
Cotton Cloth	68 (20)	.77	
Dolomite Lime	69 (20)	.41	D
Emery Corundum	176 (80)	.86	E
Glass			G
Convex D	212 (100)	.80	
Convex D	600 (316)	.80	
Convex D	932 (500)	.76	
Nonex	212 (100)	.82	
Nonex	600 (316)	.82	
Nonex	932 (500)	.78	
Smooth	32-200 (0-93)	.92-.94	
Granite	70 (21)	.45	
Gravel	100 (38)	.28	
Gypsum	68 (20)	.80-.90	
Ice			I
Smooth	32 (0)	.97	
Rough	32 (0)	.98	
Lacquer			L
Black	200 (93)	.96	
Blue, on Al Foil	100 (38)	.78	
Clear, on Al Foil (2 coats)	200 (93)	.08 (.09)	
Clear, on Bright Cu	200 (93)	.66	
Clear, on Tarnished Cu	200 (93)	.64	
Red, on Al Foil (2 coats)	100 (38)	.61 (.74)	
White	200 (93)	.95	
White, on Al Foil (2 coats)	100 (38)	.69 (.88)	
Yellow, on Al Foil (2 coats)	100 (38)	.57 (.79)	
Lime Mortar	100-500 (38-260)	.90-.92	
Limestone	100 (38)	.95	
Marble			M
White	100 (38)	.95	
Smooth, White	100 (38)	.56	
Polished Gray	100 (38)	.75	
Mica	100 (38)	.75	
Oil on Nickel			O
0.001 Film	72 (22)	.27	
0.002 Film	72 (22)	.46	
0.005 Film	72 (22)	.72	
Thick Film	72 (22)	.82	
Oil, Linseed			
On Al Foil, uncoated	250 (121)	.09	

	MATERIAL	TEMP °F (°C)	ε-EMISSIVITY
	On Al Foil, 1 coat	250 (121)	.56
	On Al Foil, 2 coats	250 (121)	.51
	On Polished Iron, .001 Film	100 (38)	.22
	On Polished Iron, .002 Film	100 (38)	.45
	On Polished Iron, .004 Film	100 (38)	.65
	On Polished Iron, Thick Film	100 (38)	.83
P	**Paints**		
	Blue, Cu_2O_3	75 (24)	.94
	Black, CuO	75 (24)	.96
	Green, Cu_2O_3	75 (24)	.92
	Red, Fe_2O_3	75 (24)	.91
	White, Al_2O_3	75 (24)	.94
	White, Y_2O_3	75 (24)	.90
	White, ZnO	75 (24)	.95
	White, $MgCO_3$	75 (24)	.91
	White ZrO_2	75 (24)	.95
	White, ThO_2	75 (24)	.90
	White, MgO	75 (24)	.91
	White $PbCO_3$	75 (24)	.93
	Yellow, PbO	75 (24)	.90
	Yellow, $PbCrO_4$	75 (24)	.93
	Paints, Aluminum	100 (38)	.27-.67
	10% Al	100 (38)	.52
	26% Al	100 (38)	.30
	Dow XP-310	200 (93)	.22
	Paints, Bronze	Low	.34-80
	Gum Varnish (2 coats)	70 (21)	.53
	Gum Varnish (3 coats)	70 (21)	.50
	Cellulose Binder (2 coats)	70 (21)	.34
	Paints, Oil		
	All colors	200 (93)	.92-.96
	Black	200 (93)	.92
	Black Gloss	70 (21)	.90
	Camouflage Green	125 (52)	.85
	Flat Black	80 (27)	.88
	Flat White	80 (27)	.91
	Grey-Green	70 (21)	.95
	Green	200 (93)	.95
	Lamp Black	209 (98)	.96
	Red	200 (93)	.95
	White	200 (93)	.94

MATERIAL	TEMP °F (°C)	ε-EMISSIVITY	
Quartz, Rough, Fused	70 (21)	.93	Q
Glass, 1.98 mm	540 (282)	.90	
Glass, 1.98 mm	1540 (838)	.41	
Glass, 6.88 mm	540 (282)	.93	
Glass, 6.88 mm	1540 (838)	.47	
Opaque	570 (299)	.92	
Opaque	1540 (838)	.68	
Red Lead	212 (100)	.93	R
Rubber			
Hard	74 (23)	.94	
Soft, Gray	76 (24)	.86	
Sand	68 (20)	.76	S
Sandstone	100 (38)	.67	
Sandstone, Red	100 (38)	.60-.83	
Sawdust	68 (20)	.75	
Shale	68 (20)	.69	
Silica			
Glazed	1832 (1000)	.85	
Unglazed	2012 (1100)	.75	
Silicon Carbide	300-1200 (149-649)	.83-.96	
Silk Cloth	68 (20)	.78	
Slate	100 (38)	.67-.80	
Snow			
Fine Particles	20 (-7)	.82	
Granular	18 (-8)	.89	
Soil			
Surface	100 (38)	.38	
Black Loam	68 (20)	.66	
Plowed Field	68 (20)	.38	
Soot			
Acetylene	75 (24)	.97	
Camphor	75 (24)	.94	
Candle	250 (121)	.95	
Coal	68 (20)	.95	
Stonework	100 (38)	.93	
Water	100 (38)	.67	W
Waterglass	68 (20)	.96	
Wood	Low	.80-.90	
Beech, Planed	158 (70)	.94	
Oak, Planed	100 (38)	.91	
Spruce, Sanded	100 (38)	.89	

Glossary

A

Absolute zero: Temperature at which thermal energy is at a minimum. Defined as 0 Kelvin or 0 Rankine (-273.15 °C or -459.67°F).

Absorptivity: The fraction of incident radiation absorbed by a surface, α.

Accuracy: Closeness of a reading or indication of a measurement device to the actual value of the quantity being measured.

Ambient compensation: The design of an instrument such that changes in ambient temperature do not affect the readings of the instrument.

Ambient temperature: The average or mean temperature of the surrounding air which comes in contact with the equipment and instruments under test.

Ampere (amp): A unit used to define the rate of flow of electricity (current) in an electrical circuit; units are one coulomb ($6.25x10^{18}$ electrons) per second. Symbolized by A.

American National Standards Institute (ANSI): The United States standards body responsible for designating standards developed by other organizations as national standards.

B

Blackbody: A theoretical object that radiates the maximum amount of energy at a given temperature, and absorbs all the energy incident upon it. A blackbody is not necessarily black. (The name blackbody was chosen because the color black is defined as the total absorption of light energy.)

Boiling point: The temperature at which a substance in the liquid phase transforms to the gaseous phase. Commonly refers to the boiling point of water, 100°C (212°F).

Bolometer: Infrared thermometer detector consisting of a resistance thermometer arranged for response to radiation.

BTU: British thermal unit, the amount of energy required to raise one pound of water one degree Fahrenheit.

C

Calibration: The process of adjusting an instrument or compiling a deviation chart so that its reading can be correlated to the actual value being measured.

Calorie: Measure of thermal energy, defined as the amount of heat required to raise one gram of water one degree Celsius at 15°C.

Celsius (Centigrade): A temperature scale defined by 0 °C at the ice point and 100°C at the boiling point of water.

Color code: The ANSI established color code for thermocouple (and infrared thermocouples) wires in which the negative lead is always red. Color code for base metal thermocouples is yellow for Type K, black for Type J, purple for Type E and blue for Type T.

Common-mode rejection ratio: The ability of an instrument to reject interference from a common voltage at its input terminals with relation to ground, usually expressed in decibels (dB).

Compensating alloys: Alloys used to connect thermocouples and IR thermocouples to instrumentation. These alloys are selected to have similar thermal electric properties as the thermocouple alloys over a limited temperature range.

Compensated connector: A connector made of thermocouple alloys used to connect thermocouple and IR thermocouple probes and wires.

CPS: Cycles per second, also Hertz (Hz).

Cryogenics: The measurement of very low temperatures, i.e., below -200°C.

Current: The rate of flow of electricity. The unit is the ampere (A), which equals one coulomb per second.

D

Degree: An incremental value in a temperature scale.

Diffuse emitter: A surface that emits radiation equally in all directions.

DIN: Deutsche Industrial Norms, a German agency that sets engineering and dimensional standards that now have worldwide acceptance.

Drift: A change in an instrument's reading or setpoint value over extended periods due to factors such as time, line voltage, or ambient temperature effects.

Dual element sensor: A sensor assembly with two independent sensing elements.

E

Electromotive force (EMF): A measure of voltage in an electrical circuit.

Electromagnetic interference (EMI): electrical noise induced upon signal wires with the possible effect of obscuring the instrument signal.

Emissive power: Rate at which radiation is emitted from a surface, per unit surface area per unit wavelength.

Emissivity/emittivity: The ratio of energy emitted by a surface to the energy emitted by a blackbody at the same temperature, symbolized by ε. Emissivity refers to an overall property of a substance, whereas emittvity refers to a particular surface's characteristics.

Error: The difference between the correct of desired value and the actual read or value taken.

F

Fahrenheit: A temperature scale define by 32°F at the ice point and 212°F at the boiling point of water at sea level.

Fiber optic radiation thermometer: Radiation thermometer that uses a fiber optic probe to separate the detector, housing, and electronics from the radiation gathering point itself. Used to measure temperature in hard-to-reach places or in hostile conditions.

Field of view: A volume in space defined by an angular cone extending from the focal plane of an instrument.

Freezing point: The temperature at which a substance goes from the liquid phase to the solid phase.

Frequency: The number of cycles over a specified time period over which an event occurs. For electromagnetic radiation, normally symbolized by υ.

G

Gain: The amount of amplification used in an electrical circuit.

Ground: The electrical neutral line having the same potential as the surrounding earth; the negative side of a direct current power system; the reference point for an electrical system.

H

Heat: Thermal energy, typically expressed in calories or BTUs.

Heat transfer: The process of thermal energy flowing from a body of high energy to a body of lower energy via conduction, convection, and/or radiation.

Hertz (Hz): Unit of frequency, defined in cycles per second.

I

Ice point: The temperature at which pure water freezes, 0°C, 32°F, 273.15°K.

Impedance: The total opposition to electrical flow.

Infrared (IR): A range of the electromagnetic spectrum extending beyond red visible light from 760 nanometers to 1000 microns.

Infrared thermocouple: Radiation thermometer whose output simulates that of a standard type thermocouple, typically over a more limited temperature range.

Interchangeability error: A measurement error that can occur if two or more sensors are used to make the same measurement. Caused by slight variations from sensor to sensor.

Intrinsically safe: An instrument in which electrical energy is limited such that it will not spark or otherwise ignite a flammable mixture.

ISA: Formerly the Instrument Society of America, now referred to as the International Society for Measurement & Control.

J

Joule: Basic unit of thermal energy.

Junction: The point in a thermocouple where the two dissimilar metals are joined.

K

Kelvin: Absolute temperature scale based on the Celsius scale, but with zero K defined at absolute zero. 0°C corresponds to 273.15°K.

L

Linearity: The deviation of an instrument's response from a straight line.

Linescanner: Device that uses a series of moving mirrors to measure temperature or other properties at various points across a moving web or surface.

Loop resistance: The total resistance of a complete electrical circuit.

M

Measuring junction: The thermocouple junction referred to as the hot junction that is used to measure an unknown temperature.

Melting point: The temperature at which a substance transforms from a solid phase to a liquid phase.

Micron (μm): One millionth of a meter.

Milliamp (mA): One thousandth of an ampere.

Millivolt (mV): One thousandth of a volt.

N

N = *N factor (= 14388/(λT))*

Narrow-band radiation thermometer: Radiation thermometer that measures radiation in a tightly controlled range of wavelengths, typically determined by the optical filter used.

Noise: Any unwanted electrical interference on a signal wire.

Normal-mode rejection ratio: The ability of an instrument to reject electrical interference across its input terminals, normally of line frequency (50-60 Hz).

O

Ohmeter: A device used to measure electrical resistance.

Optical isolation: Two networks or circuits in which an

LED transmitter and receiver are used to maintain electrical discontinuity between the circuits.

Optical pyrometer: Infrared thermometer that measures the temperature of very hot objects by the visible wavelength radiation given off.

P

Phase: A time-based relationship between a periodic function and a reference.

Photon detector: Radiation thermometer detector that releases electric charges in response to incident radiation.

Polarity: In electricity, the quality of having two oppositely charged poles, one positive and one negative.

Power supply: A separate unit or part of a circuit that provides power to the rest of a circuit.

Primary standard: The standard reference units and physical constants maintained by the National Institute of Standards & Technology (NIST) upon which all measurement units in the United States are based.

Pyroelectric detector: Radiation thermometer detector that changes surface charge in response to received radiation.

Pyrometer: Device used to measure the infrared radiation (hence temperature) given off by a body or surface.

R

Radiation: The movement of energy in the form of electromagnetic waves.

Range: An area between two limits within which a quantity is measured, stated in terms of a lower and upper limit.

Rankine: Absolute temperature scale based on the Fahrenheit scale, but with zero R defined at absolute zero. 0°F corresponds to 459.67°R.

Reference junction: The cold junction in a thermocouple circuit that is held constant at a known or measured temperature.

Reflectivity/reflectance: The fraction of incident radiation reflected by an object or surface.

Radio frequency interference (RFI): Noise induced upon signal wires by ambient radio-frequency electromagnetic radiation with the effect of obscuring the instrument signal.

Repeatability: The ability of an instrument to give the same output or reading under repeated, identical conditions.

Resistance: The resistance to the flow of electric current, measured in ohms, Ω.

S

Secondary standard: A standard of unit measurement derived from a primary standard.

Sensitivity: The minimum change in a physical variable to which an instrument can respond.

Span: The difference between the upper and lower limits of a range, expressed in the same units as the range.

Spectral filter: A filter that allows only a specific bandwidth of the electromagnetic spectrum to pass, i.e., 4-8 micron infrared radiation.

Spot size: The diameter of the circle formed by the cross section of the field of view of an optical instrument at a given distance.

Stability: The ability of an instrument or sensor to maintain a consistent output when a constant input is applied.

Sterling cycle: Thermodynamic cycle commonly used to cool thermographic detectors.

T

Thermal detector: Radiation thermometer detector that generates a signal based on the heat energy absorbed.

Thermocouple: The junction of two dissimilar metals through which a measurable current flows depending on the temperature difference between the two junctions.

Thermography: The presentation and interpretation of two-dimensional temperature pictures.

Thermometry: The science of temperature measurement.

Thermopile: an arrange of multiple thermocouples in series such that the thermoelectric output is amplified.

Thermowell: A closed-end tube designed to protect a temperature sensor from harsh process conditions.

Transmittance/transmissivity: The fraction of incident radiation passed through an object.

Two-color pyrometer: A radiation thermometer that measures the radiation output of a surface at two wavelengths, thus reducing any effects of emissivity variation with wavelength.

V

Volt (V): The electrical potential difference between two points in a circuit. One volt is the potential needed to move one coulomb of charge between two points while using one joule of energy.

W

Wavelength: Distance, from peak to peak, of any waveform. For electromagnetic radiation in the infrared region, typically measured in microns and symbolized by λ.

Working standard: A standard of unit measurement calibrated from either a primary or secondary standard which is used to calibrate other devices or make comparison measurements.

Z

Zero offset: The non-zero output of an instrument, expressed in units of measure, under conditions of true zero.

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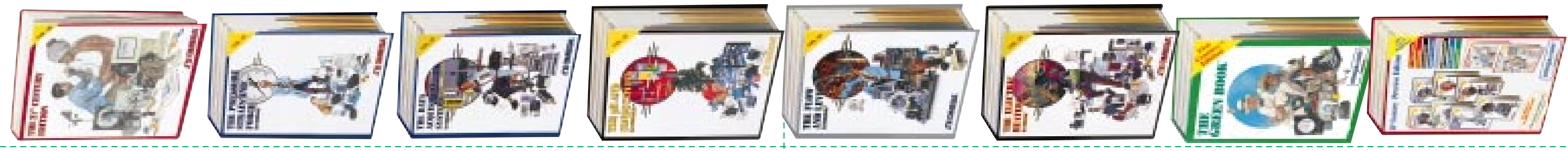

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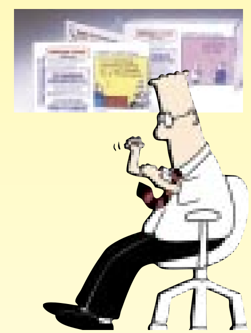

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