
Infrared theory

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1 About FLIR Systems

FLIR Systems was established in 1978 to pioneer the development of high-performance infrared imaging systems, and is the world leader in the design, manufacture, and marketing of thermal imaging systems for a wide variety of commercial, industrial, and government applications. Today, FLIR Systems embraces five major companies with outstanding achievements in infrared technology since 1958—the Swedish AGEMA Infrared Systems (formerly AGA Infrared Systems), the three United States companies Indigo Systems, FSI, and Inframetrics, and the French company Cedip.

Since 2007, FLIR Systems has acquired several companies with world-leading expertise in sensor technologies:

- Exttech Instruments (2007)
- Ifara Tecnologías (2008)
- Salvador Imaging (2009)
- OmniTech Partners (2009)
- Directed Perception (2009)
- Raymarine (2010)
- ICx Technologies (2010)
- TackTick Marine Digital Instruments (2011)
- Aerius Photonics (2011)
- Lorex Technology (2012)
- Traficon (2012)
- MARSS (2013)
- DigitalOptics micro-optics business (2013)

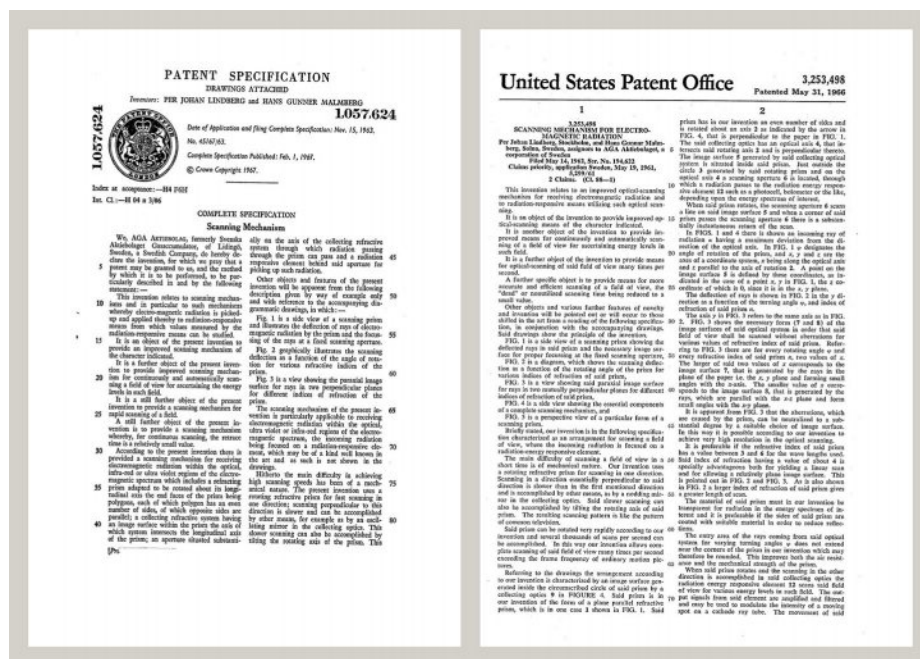


Figure 1.1 Patent documents from the early 1960s

The company has sold more than 350,000 infrared cameras worldwide for applications such as predictive maintenance, R & D, non-destructive testing, process control and automation, and machine vision, among many others.

FLIR Systems has three manufacturing plants in the United States (Portland, OR, Boston, MA, Santa Barbara, CA) and one in Sweden (Stockholm). Since 2007 there is also a manufacturing plant in Tallinn, Estonia. Direct sales offices in Belgium, Brazil, China, France, Germany, Great Britain, Hong Kong, Italy, Japan, Korea, Sweden, and the USA—together with a worldwide network of agents and distributors—support our international customer base.

FLIR Systems is at the forefront of innovation in the infrared camera industry. We anticipate market demand by constantly improving our existing cameras and developing new ones. The company has set milestones in product design and development such as the introduction of the first battery-operated portable camera for industrial inspections, and the first uncooled infrared camera, to mention just two innovations.



Figure 1.2 LEFT: Thermovision Model 661 from 1969. The camera weighed approximately 25 kg (55 lb.), the oscilloscope 20 kg (44 lb.), and the tripod 15 kg (33 lb.). The operator also needed a 220 VAC generator set, and a 10 L (2.6 US gallon) jar with liquid nitrogen. To the left of the oscilloscope the Polaroid attachment (6 kg/13 lb.) can be seen. RIGHT: FLIR One, which was launched in January 2014, is a slide-on attachment that gives iPhones thermal imaging capabilities. Weight: 90 g (3.2 oz.).

FLIR Systems manufactures all vital mechanical and electronic components of the camera systems itself. From detector design and manufacturing, to lenses and system electronics, to final testing and calibration, all production steps are carried out and supervised by our own engineers. The in-depth expertise of these infrared specialists ensures the accuracy and reliability of all vital components that are assembled into your infrared camera.

1.1 More than just an infrared camera

At FLIR Systems we recognize that our job is to go beyond just producing the best infrared camera systems. We are committed to enabling all users of our infrared camera systems to work more productively by providing them with the most powerful camera–software combination. Especially tailored software for predictive maintenance, R & D, and process monitoring is developed in-house. Most software is available in a wide variety of languages.

We support all our infrared cameras with a wide variety of accessories to adapt your equipment to the most demanding infrared applications.

1.2 Sharing our knowledge

Although our cameras are designed to be very user-friendly, there is a lot more to thermography than just knowing how to handle a camera. Therefore, FLIR Systems has founded the Infrared Training Center (ITC), a separate business unit, that provides certified training courses. Attending one of the ITC courses will give you a truly hands-on learning experience.

The staff of the ITC are also there to provide you with any application support you may need in putting infrared theory into practice.

1.3 Supporting our customers

FLIR Systems operates a worldwide service network to keep your camera running at all times. If you discover a problem with your camera, local service centers have all the equipment and expertise to solve it within the shortest possible time. Therefore, there is no need to send your camera to the other side of the world or to talk to someone who does not speak your language.

1.4 A few images from our facilities

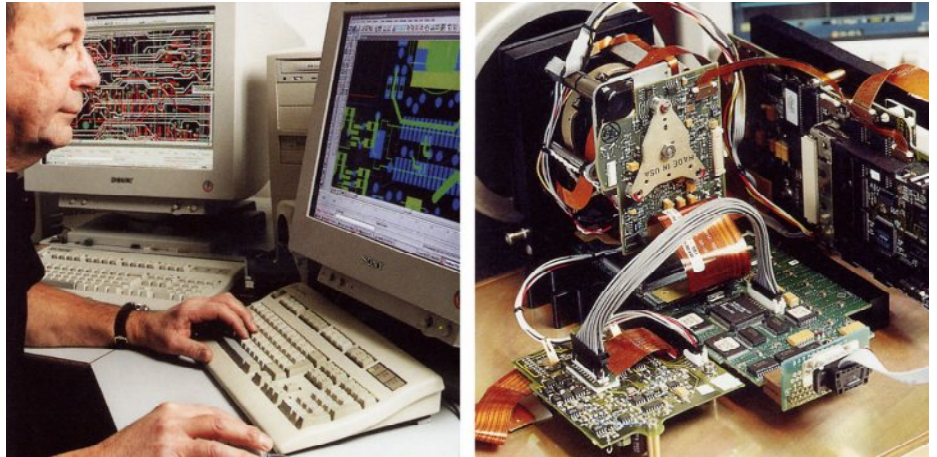


Figure 1.3 LEFT: Development of system electronics; RIGHT: Testing of an FPA detector



Figure 1.4 LEFT: Diamond turning machine; RIGHT: Lens polishing

2.1 Introduction

An infrared camera measures and images the emitted infrared radiation from an object. The fact that radiation is a function of object surface temperature makes it possible for the camera to calculate and display this temperature.

However, the radiation measured by the camera does not only depend on the temperature of the object but is also a function of the emissivity. Radiation also originates from the surroundings and is reflected in the object. The radiation from the object and the reflected radiation will also be influenced by the absorption of the atmosphere.

To measure temperature accurately, it is therefore necessary to compensate for the effects of a number of different radiation sources. This is done on-line automatically by the camera. The following object parameters must, however, be supplied for the camera:

- The emissivity of the object
- The reflected apparent temperature
- The distance between the object and the camera
- The relative humidity
- Temperature of the atmosphere

2.2 Emissivity

The most important object parameter to set correctly is the emissivity which, in short, is a measure of how much radiation is emitted from the object, compared to that from a perfect blackbody of the same temperature.

Normally, object materials and surface treatments exhibit emissivity ranging from approximately 0.1 to 0.95. A highly polished (mirror) surface falls below 0.1, while an oxidized or painted surface has a higher emissivity. Oil-based paint, regardless of color in the visible spectrum, has an emissivity over 0.9 in the infrared. Human skin exhibits an emissivity 0.97 to 0.98.

Non-oxidized metals represent an extreme case of perfect opacity and high reflexivity, which does not vary greatly with wavelength. Consequently, the emissivity of metals is low – only increasing with temperature. For non-metals, emissivity tends to be high, and decreases with temperature.

2.2.1 Finding the emissivity of a sample

2.2.1.1 Step 1: Determining reflected apparent temperature

Use one of the following two methods to determine reflected apparent temperature:

2.2.1.1.1 Method 1: Direct method

Follow this procedure:

1. Look for possible reflection sources, considering that the incident angle = reflection angle ($a = b$).

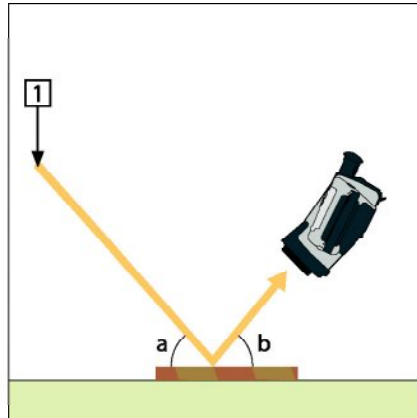


Figure 2.1 1 = Reflection source

2. If the reflection source is a spot source, modify the source by obstructing it using a piece of cardboard.

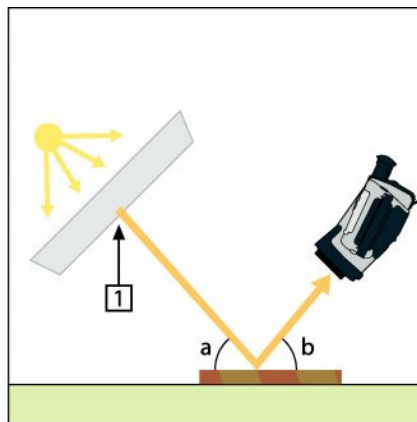


Figure 2.2 1 = Reflection source

3. Measure the radiation intensity (= apparent temperature) from the reflecting source using the following settings:

- Emissivity: 1.0
- D_{obj} : 0

You can measure the radiation intensity using one of the following two methods:

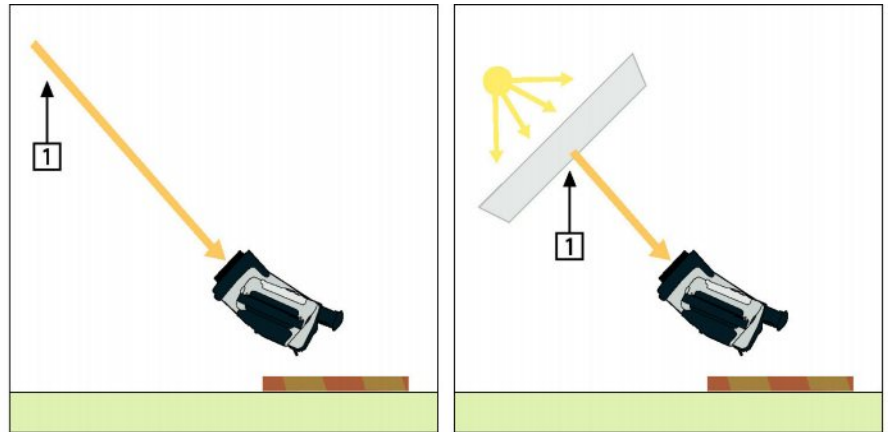


Figure 2.3 1 = Reflection source



NOTE

Using a thermocouple to measure reflected apparent temperature is not recommended for two important reasons:

- A thermocouple does not measure radiation intensity
- A thermocouple requires a very good thermal contact to the surface, usually by gluing and covering the sensor by a thermal isolator.

2.2.1.1.2 Method 2: Reflector method

Follow this procedure:

1. Crumble up a large piece of aluminum foil.
2. Uncrumble the aluminum foil and attach it to a piece of cardboard of the same size.
3. Put the piece of cardboard in front of the object you want to measure. Make sure that the side with aluminum foil points to the camera.
4. Set the emissivity to 1.0.
5. Measure the apparent temperature of the aluminum foil and write it down.

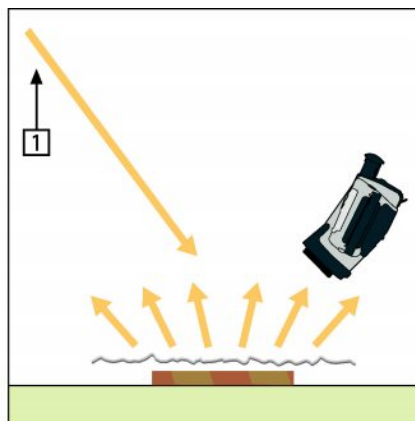


Figure 2.4 Measuring the apparent temperature of the aluminum foil.

2.2.1.2 Step 2: Determining the emissivity

Follow this procedure:

1. Select a place to put the sample.
2. Determine and set reflected apparent temperature according to the previous procedure.
3. Put a piece of electrical tape with known high emissivity on the sample.
4. Heat the sample at least 20 K above room temperature. Heating must be reasonably even.
5. Focus and auto-adjust the camera, and freeze the image.
6. Adjust *Level* and *Span* for best image brightness and contrast.
7. Set emissivity to that of the tape (usually 0.97).
8. Measure the temperature of the tape using one of the following measurement functions:
 - *Isotherm* (helps you to determine both the temperature and how evenly you have heated the sample)
 - *Spot* (simpler)
 - *Box Avg* (good for surfaces with varying emissivity).
9. Write down the temperature.
10. Move your measurement function to the sample surface.
11. Change the emissivity setting until you read the same temperature as your previous measurement.
12. Write down the emissivity.



NOTE

- Avoid forced convection
- Look for a thermally stable surrounding that will not generate spot reflections
- Use high quality tape that you know is not transparent, and has a high emissivity you are certain of
- This method assumes that the temperature of your tape and the sample surface are the same. If they are not, your emissivity measurement will be wrong.

2.3 Reflected apparent temperature

This parameter is used to compensate for the radiation reflected in the object. If the emissivity is low and the object temperature relatively far from that of the reflected it will be important to set and compensate for the reflected apparent temperature correctly.

2.4 Distance

The distance is the distance between the object and the front lens of the camera. This parameter is used to compensate for the following two facts:

- That radiation from the target is absorbed by the atmosphere between the object and the camera.
- That radiation from the atmosphere itself is detected by the camera.

2.5 Relative humidity

The camera can also compensate for the fact that the transmittance is also dependent on the relative humidity of the atmosphere. To do this set the relative humidity to the correct value. For short distances and normal humidity the relative humidity can normally be left at a default value of 50%.

2.6 Other parameters

In addition, some cameras and analysis programs from FLIR Systems allow you to compensate for the following parameters:

- Atmospheric temperature – *i.e.* the temperature of the atmosphere between the camera and the target
- External optics temperature – *i.e.* the temperature of any external lenses or windows used in front of the camera

- External optics transmittance – *i.e.* the transmission of any external lenses or windows used in front of the camera

Before the year 1800, the existence of the infrared portion of the electromagnetic spectrum wasn't even suspected. The original significance of the infrared spectrum, or simply 'the infrared' as it is often called, as a form of heat radiation is perhaps less obvious today than it was at the time of its discovery by Herschel in 1800.



Figure 3.1 Sir William Herschel (1738–1822)

The discovery was made accidentally during the search for a new optical material. Sir William Herschel – Royal Astronomer to King George III of England, and already famous for his discovery of the planet Uranus – was searching for an optical filter material to reduce the brightness of the sun's image in telescopes during solar observations. While testing different samples of colored glass which gave similar reductions in brightness he was intrigued to find that some of the samples passed very little of the sun's heat, while others passed so much heat that he risked eye damage after only a few seconds' observation.

Herschel was soon convinced of the necessity of setting up a systematic experiment, with the objective of finding a single material that would give the desired reduction in brightness as well as the maximum reduction in heat. He began the experiment by actually repeating Newton's prism experiment, but looking for the heating effect rather than the visual distribution of intensity in the spectrum. He first blackened the bulb of a sensitive mercury-in-glass thermometer with ink, and with this as his radiation detector he proceeded to test the heating effect of the various colors of the spectrum formed on the top of a table by passing sunlight through a glass prism. Other thermometers, placed outside the sun's rays, served as controls.

As the blackened thermometer was moved slowly along the colors of the spectrum, the temperature readings showed a steady increase from the violet end to the red end. This was not entirely unexpected, since the Italian researcher, Landriani, in a similar experiment in 1777 had observed much the same effect. It was Herschel, however, who was the first to recognize that there must be a point where the heating effect reaches a maximum, and that measurements confined to the visible portion of the spectrum failed to locate this point.



Figure 3.2 Marsilio Landriani (1746–1815)

Moving the thermometer into the dark region beyond the red end of the spectrum, Herschel confirmed that the heating continued to increase. The maximum point, when he found it, lay well beyond the red end – in what is known today as the 'infrared wavelengths'.

When Herschel revealed his discovery, he referred to this new portion of the electromagnetic spectrum as the 'thermometrical spectrum'. The radiation itself he sometimes referred to as 'dark heat', or simply 'the invisible rays'. Ironically, and contrary to popular opinion, it wasn't Herschel who originated the term 'infrared'. The word only began to appear in print around 75 years later, and it is still unclear who should receive credit as the originator.

Herschel's use of glass in the prism of his original experiment led to some early controversies with his contemporaries about the actual existence of the infrared wavelengths. Different investigators, in attempting to confirm his work, used various types of glass indiscriminately, having different transparencies in the infrared. Through his later experiments, Herschel was aware of the limited transparency of glass to the newly-discovered thermal radiation, and he was forced to conclude that optics for the infrared would probably be doomed to the use of reflective elements exclusively (i.e. plane and curved mirrors). Fortunately, this proved to be true only until 1830, when the Italian investigator, Melloni, made his great discovery that naturally occurring rock salt (NaCl) – which was available in large enough natural crystals to be made into lenses and prisms – is remarkably transparent to the infrared. The result was that rock salt became the principal infrared optical material, and remained so for the next hundred years, until the art of synthetic crystal growing was mastered in the 1930's.



Figure 3.3 Macedonio Melloni (1798–1854)

Thermometers, as radiation detectors, remained unchallenged until 1829, the year Nobili invented the thermocouple. (Herschel's own thermometer could be read to 0.2 °C (0.036 °F), and later models were able to be read to 0.05 °C (0.09 °F)). Then a breakthrough occurred; Melloni connected a number of thermocouples in series to form the first thermopile. The new device was at least 40 times as sensitive as the best thermometer of the day for detecting heat radiation – capable of detecting the heat from a person standing three meters away.

The first so-called 'heat-picture' became possible in 1840, the result of work by Sir John Herschel, son of the discoverer of the infrared and a famous astronomer in his own right. Based upon the differential evaporation of a thin film of oil when exposed to a heat pattern focused upon it, the thermal image could be seen by reflected light where the interference effects of the oil film made the image visible to the eye. Sir John also managed to obtain a primitive record of the thermal image on paper, which he called a 'thermograph'.



Figure 3.4 Samuel P. Langley (1834–1906)

The improvement of infrared-detector sensitivity progressed slowly. Another major breakthrough, made by Langley in 1880, was the invention of the bolometer. This consisted of a thin blackened strip of platinum connected in one arm of a Wheatstone bridge circuit upon which the infrared radiation was focused and to which a sensitive galvanometer responded. This instrument is said to have been able to detect the heat from a cow at a distance of 400 meters.

An English scientist, Sir James Dewar, first introduced the use of liquefied gases as cooling agents (such as liquid nitrogen with a temperature of -196°C (-320.8°F)) in low temperature research. In 1892 he invented a unique vacuum insulating container in which it is possible to store liquefied gases for entire days. The common 'thermos bottle', used for storing hot and cold drinks, is based upon his invention.

Between the years 1900 and 1920, the inventors of the world 'discovered' the infrared. Many patents were issued for devices to detect personnel, artillery, aircraft, ships – and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 war, when both sides had research programs devoted to the military exploitation of the infrared. These programs included experimental systems for enemy intrusion/detection, remote temperature sensing, secure communications, and 'flying torpedo' guidance. An infrared search system tested during this period was able to detect an approaching airplane at a distance of 1.5 km (0.94 miles), or a person more than 300 meters (984 ft.) away.

The most sensitive systems up to this time were all based upon variations of the bolometer idea, but the period between the two wars saw the development of two revolutionary new infrared detectors: the image converter and the photon detector. At first, the image converter received the greatest attention by the military, because it enabled an observer for the first time in history to literally 'see in the dark'. However, the sensitivity of the image converter was limited to the near infrared wavelengths, and the most interesting military targets (i.e. enemy soldiers) had to be illuminated by infrared search beams. Since this involved the risk of giving away the observer's position to a similarly-equipped enemy observer, it is understandable that military interest in the image converter eventually faded.

The tactical military disadvantages of so-called 'active' (i.e. search beam-equipped) thermal imaging systems provided impetus following the 1939–45 war for extensive secret military infrared-research programs into the possibilities of developing 'passive' (no search beam) systems around the extremely sensitive photon detector. During this period, military secrecy regulations completely prevented disclosure of the status of infrared-imaging technology. This secrecy only began to be lifted in the middle of the 1950's, and from that time adequate thermal-imaging devices finally began to be available to civilian science and industry.

4.1 Introduction

The subjects of infrared radiation and the related technique of thermography are still new to many who will use an infrared camera. In this section the theory behind thermography will be given.

4.2 The electromagnetic spectrum

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called *bands*, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiation in the different bands of the electromagnetic spectrum. They are all governed by the same laws and the only differences are those due to differences in wavelength.

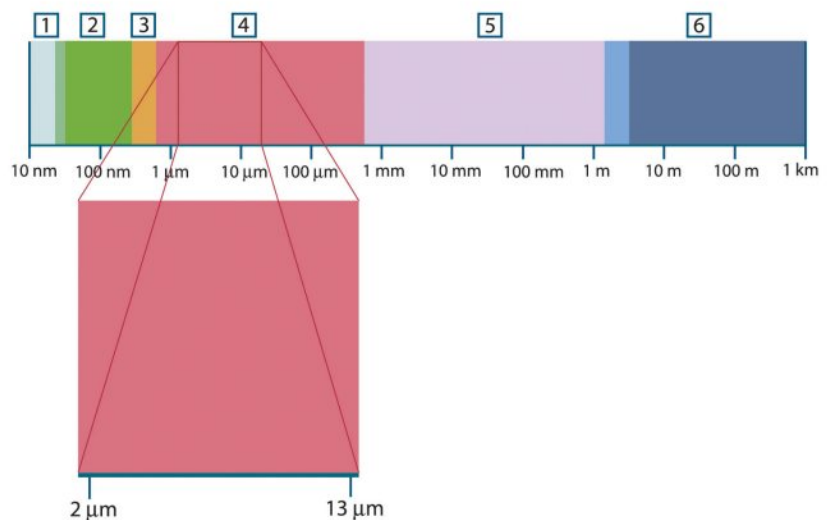


Figure 4.1 The electromagnetic spectrum. 1: X-ray; 2: UV; 3: Visible; 4: IR; 5: Microwaves; 6: Radiowaves.

Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the long-wavelength end it merges with the microwave radio wavelengths, in the millimeter range.

The infrared band is often further subdivided into four smaller bands, the boundaries of which are also arbitrarily chosen. They include: the *near infrared* (0.75–3 μm), the *middle infrared* (3–6 μm), the *far infrared* (6–15 μm) and the *extreme infrared* (15–100 μm). Although the wavelengths are given in μm (micrometers), other units are often still used to measure wavelength in this spectral region, *e.g.* nanometer (nm) and Ångström (Å).

The relationships between the different wavelength measurements is:

$$10\,000\text{ Å} = 1\,000\text{ nm} = 1\text{ μ} = 1\text{ μm}$$

4.3 Blackbody radiation

A blackbody is defined as an object which absorbs all radiation that impinges on it at any wavelength. The apparent misnomer *black* relating to an object emitting radiation is explained by Kirchhoff's Law (after *Gustav Robert Kirchhoff*, 1824–1887), which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation.



Figure 4.2 Gustav Robert Kirchhoff (1824–1887)

The construction of a blackbody source is, in principle, very simple. The radiation characteristics of an aperture in an isotherm cavity made of an opaque absorbing material represents almost exactly the properties of a blackbody. A practical application of the principle to the construction of a perfect absorber of radiation consists of a box that is light tight except for an aperture in one of the sides. Any radiation which then enters the hole is scattered and absorbed by repeated reflections so only an infinitesimal fraction can possibly escape. The blackness which is obtained at the aperture is nearly equal to a blackbody and almost perfect for all wavelengths.

By providing such an isothermal cavity with a suitable heater it becomes what is termed a *cavity radiator*. An isothermal cavity heated to a uniform temperature generates blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such cavity radiators are commonly used as sources of radiation in temperature reference standards in the laboratory for calibrating thermographic instruments, such as a FLIR Systems camera for example.

If the temperature of blackbody radiation increases to more than 525°C (977°F), the source begins to be visible so that it appears to the eye no longer black. This is the incipient red heat temperature of the radiator, which then becomes orange or yellow as the temperature increases further. In fact, the definition of the so-called *color temperature* of an object is the temperature to which a blackbody would have to be heated to have the same appearance.

Now consider three expressions that describe the radiation emitted from a blackbody.

4.3.1 Planck's law



Figure 4.3 Max Planck (1858–1947)

Max Planck (1858–1947) was able to describe the spectral distribution of the radiation from a blackbody by means of the following formula:

$$W_{\lambda b} = \frac{2\pi hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda kT}} - 1 \right)} \times 10^{-6} [\text{Watt} / \text{m}^2, \mu\text{m}]$$

where:

| | |
|-----------------|--|
| $W_{\lambda b}$ | Blackbody spectral radiant emittance at wavelength λ . |
| c | Velocity of light = 3×10^8 m/s |
| h | Planck's constant = 6.6×10^{-34} Joule sec. |
| k | Boltzmann's constant = 1.4×10^{-23} Joule/K. |
| T | Absolute temperature (K) of a blackbody. |
| λ | Wavelength (μm). |

**NOTE**

The factor 10^{-6} is used since spectral emittance in the curves is expressed in Watt/m², μm .

Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any particular Planck curve, the spectral emittance is zero at $\lambda = 0$, then increases rapidly to a maximum at a wavelength λ_{max} and after passing it approaches zero again at very long wavelengths. The higher the temperature, the shorter the wavelength at which maximum occurs.

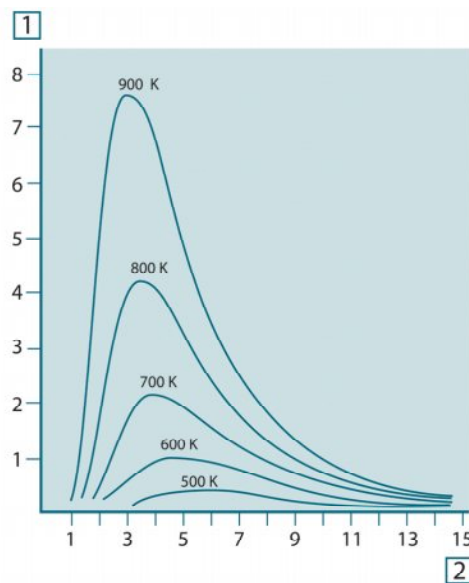


Figure 4.4 Blackbody spectral radiant emittance according to Planck's law, plotted for various absolute temperatures. 1: Spectral radiant emittance (W/cm² × 10³(μm)); 2: Wavelength (μm)

4.3.2 Wien's displacement law

By differentiating Planck's formula with respect to λ , and finding the maximum, we have:

$$\lambda_{\text{max}} = \frac{2898}{T} [\mu\text{m}]$$

This is Wien's formula (after *Wilhelm Wien*, 1864–1928), which expresses mathematically the common observation that colors vary from red to orange or yellow as the temperature of a thermal radiator increases. The wavelength of the color is the same as the wavelength calculated for λ_{max} . A good approximation of the value of λ_{max} for a given blackbody temperature is obtained by applying the rule-of-thumb $3\,000/T$ μm . Thus, a very hot star such as Sirius (11 000 K), emitting bluish-white light, radiates with the peak of spectral radiant emittance occurring within the invisible ultraviolet spectrum, at wavelength 0.27 μm .

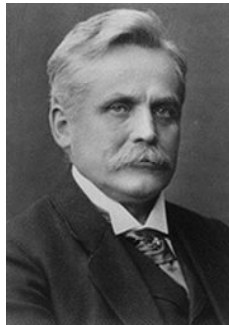


Figure 4.5 Wilhelm Wien (1864–1928)

The sun (approx. 6 000 K) emits yellow light, peaking at about 0.5 μm in the middle of the visible light spectrum.

At room temperature (300 K) the peak of radiant emittance lies at 9.7 μm , in the far infra-red, while at the temperature of liquid nitrogen (77 K) the maximum of the almost insignificant amount of radiant emittance occurs at 38 μm , in the extreme infrared wavelengths.

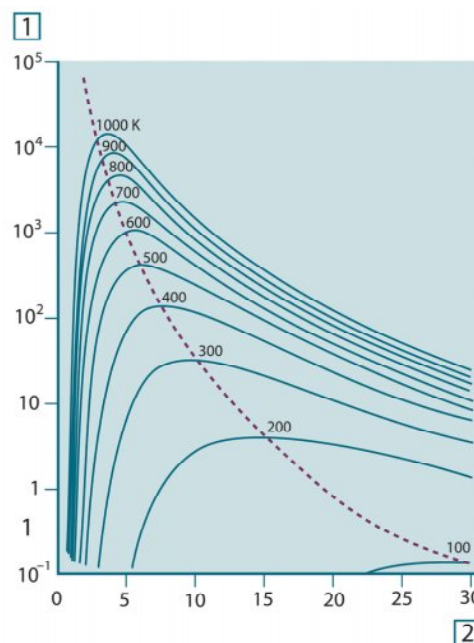


Figure 4.6 Planckian curves plotted on semi-log scales from 100 K to 1000 K. The dotted line represents the locus of maximum radiant emittance at each temperature as described by Wien's displacement law. 1: Spectral radiant emittance ($\text{W}/\text{cm}^2 (\mu\text{m})$); 2: Wavelength (μm).

4.3.3 Stefan-Boltzmann's law

By integrating Planck's formula from $\lambda = 0$ to $\lambda = \infty$, we obtain the total radiant emittance (W_b) of a blackbody:

$$W_b = \sigma T^4 \quad [\text{Watt}/\text{m}^2]$$

This is the Stefan-Boltzmann formula (after *Josef Stefan*, 1835–1893, and *Ludwig Boltzmann*, 1844–1906), which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. Graphically, W_b represents the area below the Planck curve for a particular temperature. It can be shown that the radiant emittance in the interval $\lambda = 0$ to λ_{max} is only 25% of the total, which represents about the amount of the sun's radiation which lies inside the visible light spectrum.



Figure 4.7 Josef Stefan (1835–1893), and Ludwig Boltzmann (1844–1906)

Using the Stefan-Boltzmann formula to calculate the power radiated by the human body, at a temperature of 300 K and an external surface area of approx. 2 m², we obtain 1 kW. This power loss could not be sustained if it were not for the compensating absorption of radiation from surrounding surfaces, at room temperatures which do not vary too drastically from the temperature of the body – or, of course, the addition of clothing.

4.3.4 Non-blackbody emitters

So far, only blackbody radiators and blackbody radiation have been discussed. However, real objects almost never comply with these laws over an extended wavelength region – although they may approach the blackbody behavior in certain spectral intervals. For example, a certain type of white paint may appear perfectly *white* in the visible light spectrum, but becomes distinctly *gray* at about 2 μm, and beyond 3 μm it is almost *black*.

There are three processes which can occur that prevent a real object from acting like a blackbody: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted. Since all of these factors are more or less wavelength dependent, the subscript λ is used to imply the spectral dependence of their definitions. Thus:

- The spectral absorptance α_λ = the ratio of the spectral radiant power absorbed by an object to that incident upon it.
- The spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it.
- The spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

The sum of these three factors must always add up to the whole at any wavelength, so we have the relation:

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

For opaque materials $\tau_\lambda = 0$ and the relation simplifies to:

$$\varepsilon_\lambda + \rho_\lambda = 1$$

Another factor, called the emissivity, is required to describe the fraction ε of the radiant emittance of a blackbody produced by an object at a specific temperature. Thus, we have the definition:

The spectral emissivity ε_λ = the ratio of the spectral radiant power from an object to that from a blackbody at the same temperature and wavelength.

Expressed mathematically, this can be written as the ratio of the spectral emittance of the object to that of a blackbody as follows:

$$\varepsilon_\lambda = \frac{W_{\lambda o}}{W_{\lambda b}}$$

Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance of each varies with wavelength.

- A blackbody, for which $\varepsilon_\lambda = \varepsilon = 1$
- A graybody, for which $\varepsilon_\lambda = \varepsilon = \text{constant less than } 1$

- A selective radiator, for which ε varies with wavelength

According to Kirchhoff's law, for any material the spectral emissivity and spectral absorptance of a body are equal at any specified temperature and wavelength. That is:

$$\varepsilon_{\lambda} = \alpha_{\lambda}$$

From this we obtain, for an opaque material (since $\alpha_{\lambda} + \rho_{\lambda} = 1$):

$$\varepsilon_{\lambda} + \rho_{\lambda} = 1$$

For highly polished materials ε_{λ} approaches zero, so that for a perfectly reflecting material (*i.e.* a perfect mirror) we have:

$$\rho_{\lambda} = 1$$

For a graybody radiator, the Stefan-Boltzmann formula becomes:

$$W = \varepsilon \sigma T^4 \text{ [Watt/m}^2\text{]}$$

This states that the total emissive power of a graybody is the same as a blackbody at the same temperature reduced in proportion to the value of ε from the graybody.

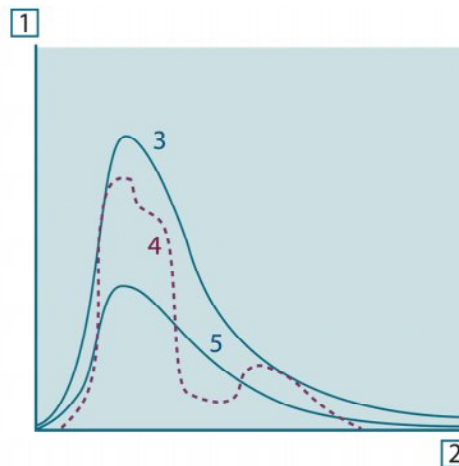


Figure 4.8 Spectral radiant emittance of three types of radiators. 1: Spectral radiant emittance; 2: Wavelength; 3: Blackbody; 4: Selective radiator; 5: Graybody.

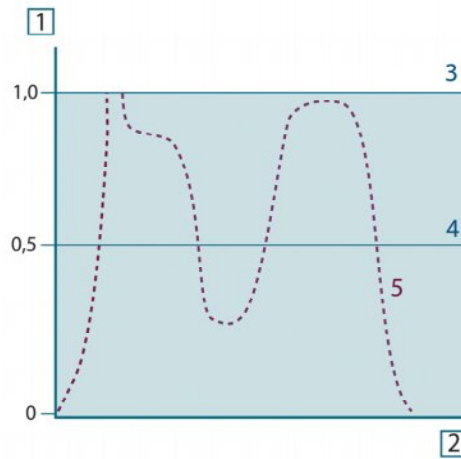


Figure 4.9 Spectral emissivity of three types of radiators. 1: Spectral emissivity; 2: Wavelength; 3: Black-body; 4: Graybody; 5: Selective radiator.

4.4 Infrared semi-transparent materials

Consider now a non-metallic, semi-transparent body – let us say, in the form of a thick flat plate of plastic material. When the plate is heated, radiation generated within its volume must work its way toward the surfaces through the material in which it is partially absorbed. Moreover, when it arrives at the surface, some of it is reflected back into the interior. The back-reflected radiation is again partially absorbed, but some of it arrives at the other surface, through which most of it escapes; part of it is reflected back again. Although the progressive reflections become weaker and weaker they must all be added up when the total emittance of the plate is sought. When the resulting geometrical series is summed, the effective emissivity of a semi-transparent plate is obtained as:

$$\varepsilon_{\lambda} = \frac{(1 - \rho_{\lambda})(1 - \tau_{\lambda})}{1 - \rho_{\lambda}\tau_{\lambda}}$$

When the plate becomes opaque this formula is reduced to the single formula:

$$\varepsilon_{\lambda} = 1 - \rho_{\lambda}$$

This last relation is a particularly convenient one, because it is often easier to measure reflectance than to measure emissivity directly.

As already mentioned, when viewing an object, the camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. To this comes a third radiation contribution from the atmosphere itself.

This description of the measurement situation, as illustrated in the figure below, is so far a fairly true description of the real conditions. What has been neglected could for instance be sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify, however, in most cases they are fortunately small enough to be neglected. In case they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, shielding off intense radiation sources etc.

Accepting the description above, we can use the figure below to derive a formula for the calculation of the object temperature from the calibrated camera output.

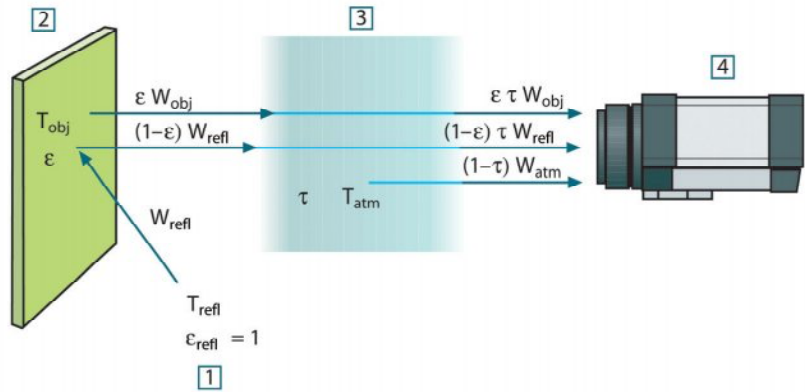


Figure 5.1 A schematic representation of the general thermographic measurement situation. 1: Surroundings; 2: Object; 3: Atmosphere; 4: Camera

Assume that the received radiation power W from a blackbody source of temperature T_{source} on short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera). We can then write (Equation 1):

$$U_{\text{source}} = CW(T_{\text{source}})$$

or, with simplified notation:

$$U_{\text{source}} = CW_{\text{source}}$$

where C is a constant.

Should the source be a graybody with emittance ϵ , the received radiation would consequently be $\epsilon W_{\text{source}}$.

We are now ready to write the three collected radiation power terms:

1. *Emission from the object* = $\epsilon\tau W_{\text{obj}}$, where ϵ is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj} .

2. *Reflected emission from ambient sources* = $(1 - \varepsilon)\tau W_{\text{refl}}$, where $(1 - \varepsilon)$ is the reflectance of the object. The ambient sources have the temperature T_{refl} .

It has here been assumed that the temperature T_{refl} is the same for all emitting surfaces within the hemisphere seen from a point on the object surface. This is of course sometimes a simplification of the true situation. It is, however, a necessary simplification in order to derive a workable formula, and T_{refl} can – at least theoretically – be given a value that represents an efficient temperature of a complex surrounding.

Note also that we have assumed that the emittance for the surroundings = 1. This is correct in accordance with Kirchhoff's law: All radiation impinging on the surrounding surfaces will eventually be absorbed by the same surfaces. Thus the emittance = 1. (Note though that the latest discussion requires the complete sphere around the object to be considered.)

3. *Emission from the atmosphere* = $(1 - \tau)\tau W_{\text{atm}}$, where $(1 - \tau)$ is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm} .

The total received radiation power can now be written (Equation 2):

$$W_{\text{tot}} = \varepsilon\tau W_{\text{obj}} + (1 - \varepsilon)\tau W_{\text{refl}} + (1 - \tau)W_{\text{atm}}$$

We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get (Equation 3):

$$U_{\text{tot}} = \varepsilon\tau U_{\text{obj}} + (1 - \varepsilon)\tau U_{\text{refl}} + (1 - \tau)U_{\text{atm}}$$

Solve Equation 3 for U_{obj} (Equation 4):

$$U_{\text{obj}} = \frac{1}{\varepsilon\tau} U_{\text{tot}} - \frac{1 - \varepsilon}{\varepsilon} U_{\text{refl}} - \frac{1 - \tau}{\varepsilon\tau} U_{\text{atm}}$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment. The voltages of the formula are:

Table 5.1 Voltages

| | |
|-------------------|--|
| U_{obj} | Calculated camera output voltage for a blackbody of temperature T_{obj} i.e. a voltage that can be directly converted into true requested object temperature. |
| U_{tot} | Measured camera output voltage for the actual case. |
| U_{refl} | Theoretical camera output voltage for a blackbody of temperature T_{refl} according to the calibration. |
| U_{atm} | Theoretical camera output voltage for a blackbody of temperature T_{atm} according to the calibration. |

The operator has to supply a number of parameter values for the calculation:

- the object emittance ε ,
- the relative humidity,
- T_{atm}
- object distance (D_{obj})
- the (effective) temperature of the object surroundings, or the reflected ambient temperature T_{refl} , and
- the temperature of the atmosphere T_{atm}

This task could sometimes be a heavy burden for the operator since there are normally no easy ways to find accurate values of emittance and atmospheric transmittance for the actual case. The two temperatures are normally less of a problem provided the surroundings do not contain large and intense radiation sources.

A natural question in this connection is: How important is it to know the right values of these parameters? It could though be of interest to get a feeling for this problem already here by looking into some different measurement cases and compare the relative

magnitudes of the three radiation terms. This will give indications about when it is important to use correct values of which parameters.

The figures below illustrates the relative magnitudes of the three radiation contributions for three different object temperatures, two emittances, and two spectral ranges: SW and LW. Remaining parameters have the following fixed values:

- $\tau = 0.88$
- $T_{\text{refl}} = +20^{\circ}\text{C}$ ($+68^{\circ}\text{F}$)
- $T_{\text{atm}} = +20^{\circ}\text{C}$ ($+68^{\circ}\text{F}$)

It is obvious that measurement of low object temperatures are more critical than measuring high temperatures since the 'disturbing' radiation sources are relatively much stronger in the first case. Should also the object emittance be low, the situation would be still more difficult.

We have finally to answer a question about the importance of being allowed to use the calibration curve above the highest calibration point, what we call extrapolation. Imagine that we in a certain case measure $U_{\text{tot}} = 4.5$ volts. The highest calibration point for the camera was in the order of 4.1 volts, a value unknown to the operator. Thus, even if the object happened to be a blackbody, i.e. $U_{\text{obj}} = U_{\text{tot}}$, we are actually performing extrapolation of the calibration curve when converting 4.5 volts into temperature.

Let us now assume that the object is not black, it has an emittance of 0.75, and the transmittance is 0.92. We also assume that the two second terms of Equation 4 amount to 0.5 volts together. Computation of U_{obj} by means of Equation 4 then results in $U_{\text{obj}} = 4.5 / 0.75 / 0.92 - 0.5 = 6.0$. This is a rather extreme extrapolation, particularly when considering that the video amplifier might limit the output to 5 volts! Note, though, that the application of the calibration curve is a theoretical procedure where no electronic or other limitations exist. We trust that if there had been no signal limitations in the camera, and if it had been calibrated far beyond 5 volts, the resulting curve would have been very much the same as our real curve extrapolated beyond 4.1 volts, provided the calibration algorithm is based on radiation physics, like the FLIR Systems algorithm. Of course there must be a limit to such extrapolations.

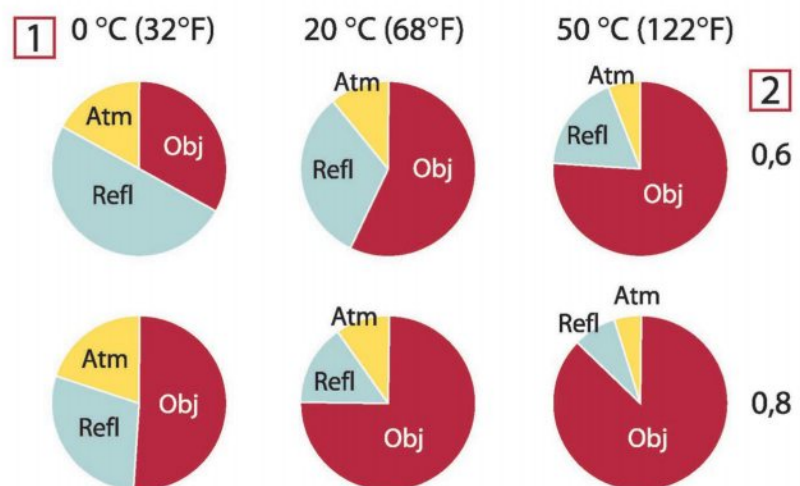


Figure 5.2 Relative magnitudes of radiation sources under varying measurement conditions (SW camera). 1: Object temperature; 2: Emittance; Obj: Object radiation; Refl: Reflected radiation; Atm: atmosphere radiation. Fixed parameters: $\tau = 0.88$; $T_{\text{refl}} = 20^{\circ}\text{C}$ ($+68^{\circ}\text{F}$); $T_{\text{atm}} = 20^{\circ}\text{C}$ ($+68^{\circ}\text{F}$).

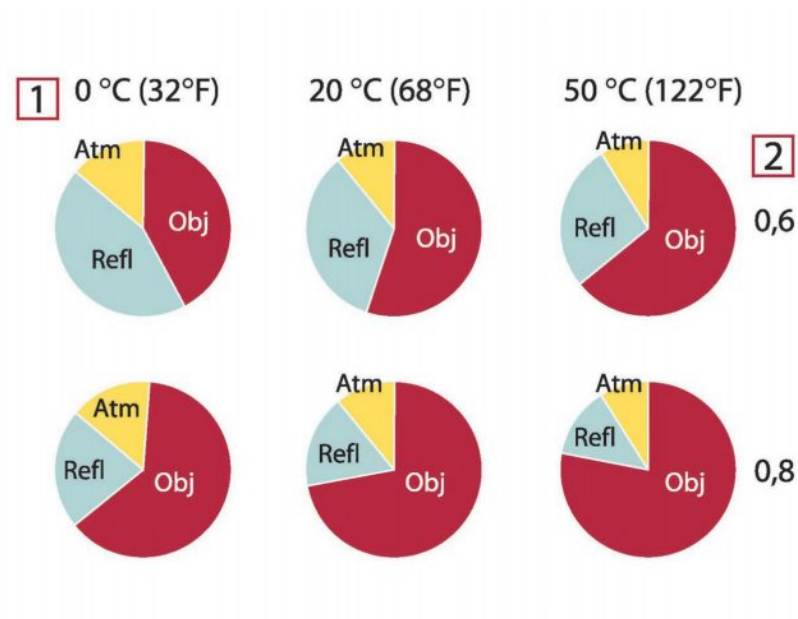


Figure 5.3 Relative magnitudes of radiation sources under varying measurement conditions (LW camera). 1: Object temperature; 2: Emittance; Obj: Object radiation; Refl: Reflected radiation; Atm: atmosphere radiation. Fixed parameters: $\tau = 0.88$; $T_{\text{refl}} = 20^{\circ}\text{C}$ (+68°F); $T_{\text{atm}} = 20^{\circ}\text{C}$ (+68°F).

This section presents a compilation of emissivity data from the infrared literature and measurements made by FLIR Systems.

6.1 References

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NOTE

The emissivity values in the table below are recorded using a shortwave (SW) camera. The values should be regarded as recommendations only and used with caution.

6.2 Tables

Table 6.1 T: Total spectrum; SW: 2–5 μm ; LW: 8–14 μm , LLW: 6.5–20 μm ; 1: Material; 2: Specification; 3: Temperature in $^{\circ}\text{C}$; 4: Spectrum; 5: Emissivity; 6: Reference

| 1 | 2 | 3 | 4 | 5 | 6 |
|-------------------|--|-------|----|----------------|----|
| 3M type 35 | Vinyl electrical tape (several colors) | < 80 | LW | ≈ 0.96 | 13 |
| 3M type 88 | Black vinyl electrical tape | < 105 | LW | ≈ 0.96 | 13 |
| 3M type 88 | Black vinyl electrical tape | < 105 | MW | < 0.96 | 13 |
| 3M type Super 33+ | Black vinyl electrical tape | < 80 | LW | ≈ 0.96 | 13 |
| Aluminum | anodized sheet | 100 | T | 0.55 | 2 |
| Aluminum | anodized, black, dull | 70 | SW | 0.67 | 9 |
| Aluminum | anodized, black, dull | 70 | LW | 0.95 | 9 |
| Aluminum | anodized, light gray, dull | 70 | SW | 0.61 | 9 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|--------------------|--|---------|-------|-----------|---|
| Aluminum | anodized, light gray, dull | 70 | LW | 0.97 | 9 |
| Aluminum | as received, plate | 100 | T | 0.09 | 4 |
| Aluminum | as received, sheet | 100 | T | 0.09 | 2 |
| Aluminum | cast, blast cleaned | 70 | SW | 0.47 | 9 |
| Aluminum | cast, blast cleaned | 70 | LW | 0.46 | 9 |
| Aluminum | dipped in HNO ₃ , plate | 100 | T | 0.05 | 4 |
| Aluminum | foil | 27 | 10 µm | 0.04 | 3 |
| Aluminum | foil | 27 | 3 µm | 0.09 | 3 |
| Aluminum | oxidized, strongly | 50–500 | T | 0.2–0.3 | 1 |
| Aluminum | polished | 50–100 | T | 0.04–0.06 | 1 |
| Aluminum | polished plate | 100 | T | 0.05 | 4 |
| Aluminum | polished, sheet | 100 | T | 0.05 | 2 |
| Aluminum | rough surface | 20–50 | T | 0.06–0.07 | 1 |
| Aluminum | roughened | 27 | 10 µm | 0.18 | 3 |
| Aluminum | roughened | 27 | 3 µm | 0.28 | 3 |
| Aluminum | sheet, 4 samples differently scratched | 70 | SW | 0.05–0.08 | 9 |
| Aluminum | sheet, 4 samples differently scratched | 70 | LW | 0.03–0.06 | 9 |
| Aluminum | vacuum deposited | 20 | T | 0.04 | 2 |
| Aluminum | weathered, heavily | 17 | SW | 0.83–0.94 | 5 |
| Aluminum bronze | | 20 | T | 0.60 | 1 |
| Aluminum hydroxide | powder | | T | 0.28 | 1 |
| Aluminum oxide | activated, powder | | T | 0.46 | 1 |
| Aluminum oxide | pure, powder (alumina) | | T | 0.16 | 1 |
| Asbestos | board | 20 | T | 0.96 | 1 |
| Asbestos | fabric | | T | 0.78 | 1 |
| Asbestos | floor tile | 35 | SW | 0.94 | 7 |
| Asbestos | paper | 40–400 | T | 0.93–0.95 | 1 |
| Asbestos | powder | | T | 0.40–0.60 | 1 |
| Asbestos | slate | 20 | T | 0.96 | 1 |
| Asphalt paving | | 4 | LLW | 0.967 | 8 |
| Brass | dull, tarnished | 20–350 | T | 0.22 | 1 |
| Brass | oxidized | 100 | T | 0.61 | 2 |
| Brass | oxidized | 70 | SW | 0.04–0.09 | 9 |
| Brass | oxidized | 70 | LW | 0.03–0.07 | 9 |
| Brass | oxidized at 600°C | 200–600 | T | 0.59–0.61 | 1 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|--------|--|-----------|----|-----------|---|
| Brass | polished | 200 | T | 0.03 | 1 |
| Brass | polished, highly | 100 | T | 0.03 | 2 |
| Brass | rubbed with 80-grit emery | 20 | T | 0.20 | 2 |
| Brass | sheet, rolled | 20 | T | 0.06 | 1 |
| Brass | sheet, worked with emery | 20 | T | 0.2 | 1 |
| Brick | alumina | 17 | SW | 0.68 | 5 |
| Brick | common | 17 | SW | 0.86–0.81 | 5 |
| Brick | Dinas silica, glazed, rough | 1100 | T | 0.85 | 1 |
| Brick | Dinas silica, refractory | 1000 | T | 0.66 | 1 |
| Brick | Dinas silica, unglazed, rough | 1000 | T | 0.80 | 1 |
| Brick | firebrick | 17 | SW | 0.68 | 5 |
| Brick | fireclay | 1000 | T | 0.75 | 1 |
| Brick | fireclay | 1200 | T | 0.59 | 1 |
| Brick | fireclay | 20 | T | 0.85 | 1 |
| Brick | masonry | 35 | SW | 0.94 | 7 |
| Brick | masonry, plastered | 20 | T | 0.94 | 1 |
| Brick | red, common | 20 | T | 0.93 | 2 |
| Brick | red, rough | 20 | T | 0.88–0.93 | 1 |
| Brick | refractory, corundum | 1000 | T | 0.46 | 1 |
| Brick | refractory, magnesite | 1000–1300 | T | 0.38 | 1 |
| Brick | refractory, strongly radiating | 500–1000 | T | 0.8–0.9 | 1 |
| Brick | refractory, weakly radiating | 500–1000 | T | 0.65–0.75 | 1 |
| Brick | silica, 95% SiO ₂ | 1230 | T | 0.66 | 1 |
| Brick | sillimanite, 33% SiO ₂ , 64% Al ₂ O ₃ | 1500 | T | 0.29 | 1 |
| Brick | waterproof | 17 | SW | 0.87 | 5 |
| Bronze | phosphor bronze | 70 | SW | 0.08 | 9 |
| Bronze | phosphor bronze | 70 | LW | 0.06 | 9 |
| Bronze | polished | 50 | T | 0.1 | 1 |
| Bronze | porous, rough | 50–150 | T | 0.55 | 1 |
| Bronze | powder | | T | 0.76–0.80 | 1 |
| Carbon | candle soot | 20 | T | 0.95 | 2 |
| Carbon | charcoal powder | | T | 0.96 | 1 |
| Carbon | graphite powder | | T | 0.97 | 1 |
| Carbon | graphite, filed surface | 20 | T | 0.98 | 2 |
| Carbon | lampblack | 20–400 | T | 0.95–0.97 | 1 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|----------------|----------------------------------|-----------|-----|-----------|---|
| Chipboard | untreated | 20 | SW | 0.90 | 6 |
| Chromium | polished | 50 | T | 0.10 | 1 |
| Chromium | polished | 500–1000 | T | 0.28–0.38 | 1 |
| Clay | fired | 70 | T | 0.91 | 1 |
| Cloth | black | 20 | T | 0.98 | 1 |
| Concrete | | 20 | T | 0.92 | 2 |
| Concrete | dry | 36 | SW | 0.95 | 7 |
| Concrete | rough | 17 | SW | 0.97 | 5 |
| Concrete | walkway | 5 | LLW | 0.974 | 8 |
| Copper | commercial, burnished | 20 | T | 0.07 | 1 |
| Copper | electrolytic, carefully polished | 80 | T | 0.018 | 1 |
| Copper | electrolytic, polished | –34 | T | 0.006 | 4 |
| Copper | molten | 1100–1300 | T | 0.13–0.15 | 1 |
| Copper | oxidized | 50 | T | 0.6–0.7 | 1 |
| Copper | oxidized to blackness | | T | 0.88 | 1 |
| Copper | oxidized, black | 27 | T | 0.78 | 4 |
| Copper | oxidized, heavily | 20 | T | 0.78 | 2 |
| Copper | polished | 50–100 | T | 0.02 | 1 |
| Copper | polished | 100 | T | 0.03 | 2 |
| Copper | polished, commercial | 27 | T | 0.03 | 4 |
| Copper | polished, mechanical | 22 | T | 0.015 | 4 |
| Copper | pure, carefully prepared surface | 22 | T | 0.008 | 4 |
| Copper | scraped | 27 | T | 0.07 | 4 |
| Copper dioxide | powder | | T | 0.84 | 1 |
| Copper oxide | red, powder | | T | 0.70 | 1 |
| Ebonite | | | T | 0.89 | 1 |
| Emery | coarse | 80 | T | 0.85 | 1 |
| Enamel | | 20 | T | 0.9 | 1 |
| Enamel | lacquer | 20 | T | 0.85–0.95 | 1 |
| Fiber board | hard, untreated | 20 | SW | 0.85 | 6 |
| Fiber board | masonite | 70 | SW | 0.75 | 9 |
| Fiber board | masonite | 70 | LW | 0.88 | 9 |
| Fiber board | particle board | 70 | SW | 0.77 | 9 |
| Fiber board | particle board | 70 | LW | 0.89 | 9 |
| Fiber board | porous, untreated | 20 | SW | 0.85 | 6 |
| Gold | polished | 130 | T | 0.018 | 1 |
| Gold | polished, carefully | 200–600 | T | 0.02–0.03 | 1 |
| Gold | polished, highly | 100 | T | 0.02 | 2 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|----------------|----------------------------------|----------|-----|-----------|---|
| Granite | polished | 20 | LLW | 0.849 | 8 |
| Granite | rough | 21 | LLW | 0.879 | 8 |
| Granite | rough, 4 different samples | 70 | SW | 0.95–0.97 | 9 |
| Granite | rough, 4 different samples | 70 | LW | 0.77–0.87 | 9 |
| Gypsum | | 20 | T | 0.8–0.9 | 1 |
| Ice: See Water | | | | | |
| Iron and steel | cold rolled | 70 | SW | 0.20 | 9 |
| Iron and steel | cold rolled | 70 | LW | 0.09 | 9 |
| Iron and steel | covered with red rust | 20 | T | 0.61–0.85 | 1 |
| Iron and steel | electrolytic | 100 | T | 0.05 | 4 |
| Iron and steel | electrolytic | 22 | T | 0.05 | 4 |
| Iron and steel | electrolytic | 260 | T | 0.07 | 4 |
| Iron and steel | electrolytic, carefully polished | 175–225 | T | 0.05–0.06 | 1 |
| Iron and steel | freshly worked with emery | 20 | T | 0.24 | 1 |
| Iron and steel | ground sheet | 950–1100 | T | 0.55–0.61 | 1 |
| Iron and steel | heavily rusted sheet | 20 | T | 0.69 | 2 |
| Iron and steel | hot rolled | 130 | T | 0.60 | 1 |
| Iron and steel | hot rolled | 20 | T | 0.77 | 1 |
| Iron and steel | oxidized | 100 | T | 0.74 | 4 |
| Iron and steel | oxidized | 100 | T | 0.74 | 1 |
| Iron and steel | oxidized | 1227 | T | 0.89 | 4 |
| Iron and steel | oxidized | 125–525 | T | 0.78–0.82 | 1 |
| Iron and steel | oxidized | 200 | T | 0.79 | 2 |
| Iron and steel | oxidized | 200–600 | T | 0.80 | 1 |
| Iron and steel | oxidized strongly | 50 | T | 0.88 | 1 |
| Iron and steel | oxidized strongly | 500 | T | 0.98 | 1 |
| Iron and steel | polished | 100 | T | 0.07 | 2 |
| Iron and steel | polished | 400–1000 | T | 0.14–0.38 | 1 |
| Iron and steel | polished sheet | 750–1050 | T | 0.52–0.56 | 1 |
| Iron and steel | rolled sheet | 50 | T | 0.56 | 1 |
| Iron and steel | rolled, freshly | 20 | T | 0.24 | 1 |
| Iron and steel | rough, plane surface | 50 | T | 0.95–0.98 | 1 |
| Iron and steel | rusted red, sheet | 22 | T | 0.69 | 4 |
| Iron and steel | rusted, heavily | 17 | SW | 0.96 | 5 |
| Iron and steel | rusty, red | 20 | T | 0.69 | 1 |
| Iron and steel | shiny oxide layer, sheet, | 20 | T | 0.82 | 1 |
| Iron and steel | shiny, etched | 150 | T | 0.16 | 1 |

Table 6.1 T: Total spectrum; SW: 2–5 μm ; LW: 8–14 μm , LLW: 6.5–20 μm ; 1: Material; 2: Specification; 3: Temperature in $^{\circ}\text{C}$; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|------------------------------|------------------------------------|----------------------------|----|----------------|----|
| Iron and steel | wrought, carefully polished | 40–250 | T | 0.28 | 1 |
| Iron galvanized | heavily oxidized | 70 | SW | 0.64 | 9 |
| Iron galvanized | heavily oxidized | 70 | LW | 0.85 | 9 |
| Iron galvanized | sheet | 92 | T | 0.07 | 4 |
| Iron galvanized | sheet, burnished | 30 | T | 0.23 | 1 |
| Iron galvanized | sheet, oxidized | 20 | T | 0.28 | 1 |
| Iron tinned | sheet | 24 | T | 0.064 | 4 |
| Iron, cast | casting | 50 | T | 0.81 | 1 |
| Iron, cast | ingots | 1000 | T | 0.95 | 1 |
| Iron, cast | liquid | 1300 | T | 0.28 | 1 |
| Iron, cast | machined | 800–1000 | T | 0.60–0.70 | 1 |
| Iron, cast | oxidized | 100 | T | 0.64 | 2 |
| Iron, cast | oxidized | 260 | T | 0.66 | 4 |
| Iron, cast | oxidized | 38 | T | 0.63 | 4 |
| Iron, cast | oxidized | 538 | T | 0.76 | 4 |
| Iron, cast | oxidized at 600 $^{\circ}\text{C}$ | 200–600 | T | 0.64–0.78 | 1 |
| Iron, cast | polished | 200 | T | 0.21 | 1 |
| Iron, cast | polished | 38 | T | 0.21 | 4 |
| Iron, cast | polished | 40 | T | 0.21 | 2 |
| Iron, cast | unworked | 900–1100 | T | 0.87–0.95 | 1 |
| Krylon Ultra-flat black 1602 | Flat black | Room temperature up to 175 | LW | ≈ 0.96 | 12 |
| Krylon Ultra-flat black 1602 | Flat black | Room temperature up to 175 | MW | ≈ 0.97 | 12 |
| Lacquer | 3 colors sprayed on Aluminum | 70 | SW | 0.50–0.53 | 9 |
| Lacquer | 3 colors sprayed on Aluminum | 70 | LW | 0.92–0.94 | 9 |
| Lacquer | Aluminum on rough surface | 20 | T | 0.4 | 1 |
| Lacquer | bakelite | 80 | T | 0.83 | 1 |
| Lacquer | black, dull | 40–100 | T | 0.96–0.98 | 1 |
| Lacquer | black, matte | 100 | T | 0.97 | 2 |
| Lacquer | black, shiny, sprayed on iron | 20 | T | 0.87 | 1 |
| Lacquer | heat-resistant | 100 | T | 0.92 | 1 |
| Lacquer | white | 100 | T | 0.92 | 2 |
| Lacquer | white | 40–100 | T | 0.8–0.95 | 1 |
| Lead | oxidized at 200 $^{\circ}\text{C}$ | 200 | T | 0.63 | 1 |
| Lead | oxidized, gray | 20 | T | 0.28 | 1 |
| Lead | oxidized, gray | 22 | T | 0.28 | 4 |
| Lead | shiny | 250 | T | 0.08 | 1 |
| Lead | unoxidized, polished | 100 | T | 0.05 | 4 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|----------------------------|-----------------------------------|-----------|----|-----------|-----------|
| Lead red | | 100 | T | 0.93 | 4 |
| Lead red, powder | | 100 | T | 0.93 | 1 |
| Leather | tanned | | T | 0.75–0.80 | 1 |
| Lime | | | T | 0.3–0.4 | 1 |
| Magnesium | | 22 | T | 0.07 | 4 |
| Magnesium | | 260 | T | 0.13 | 4 |
| Magnesium | | 538 | T | 0.18 | 4 |
| Magnesium | polished | 20 | T | 0.07 | 2 |
| Magnesium powder | | | T | 0.86 | 1 |
| Molybdenum | | 1500–2200 | T | 0.19–0.26 | 1 |
| Molybdenum | | 600–1000 | T | 0.08–0.13 | 1 |
| Molybdenum | filament | 700–2500 | T | 0.1–0.3 | 1 |
| Mortar | | 17 | SW | 0.87 | 5 |
| Mortar | dry | 36 | SW | 0.94 | 7 |
| Nextel Velvet 811-21 Black | Flat black | –60–150 | LW | > 0.97 | 10 and 11 |
| Nichrome | rolled | 700 | T | 0.25 | 1 |
| Nichrome | sandblasted | 700 | T | 0.70 | 1 |
| Nichrome | wire, clean | 50 | T | 0.65 | 1 |
| Nichrome | wire, clean | 500–1000 | T | 0.71–0.79 | 1 |
| Nichrome | wire, oxidized | 50–500 | T | 0.95–0.98 | 1 |
| Nickel | bright matte | 122 | T | 0.041 | 4 |
| Nickel | commercially pure, polished | 100 | T | 0.045 | 1 |
| Nickel | commercially pure, polished | 200–400 | T | 0.07–0.09 | 1 |
| Nickel | electrolytic | 22 | T | 0.04 | 4 |
| Nickel | electrolytic | 260 | T | 0.07 | 4 |
| Nickel | electrolytic | 38 | T | 0.06 | 4 |
| Nickel | electrolytic | 538 | T | 0.10 | 4 |
| Nickel | electroplated on iron, polished | 22 | T | 0.045 | 4 |
| Nickel | electroplated on iron, unpolished | 20 | T | 0.11–0.40 | 1 |
| Nickel | electroplated on iron, unpolished | 22 | T | 0.11 | 4 |
| Nickel | electroplated, polished | 20 | T | 0.05 | 2 |
| Nickel | oxidized | 1227 | T | 0.85 | 4 |
| Nickel | oxidized | 200 | T | 0.37 | 2 |
| Nickel | oxidized | 227 | T | 0.37 | 4 |
| Nickel | oxidized at 600°C | 200–600 | T | 0.37–0.48 | 1 |
| Nickel | polished | 122 | T | 0.045 | 4 |
| Nickel | wire | 200–1000 | T | 0.1–0.2 | 1 |
| Nickel oxide | | 1000–1250 | T | 0.75–0.86 | 1 |

Table 6.1 T: Total spectrum; SW: 2–5 μm ; LW: 8–14 μm , LLW: 6.5–20 μm ; 1: Material; 2: Specification; 3: Temperature in $^{\circ}\text{C}$; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|------------------|--------------------------------------|---------|----|-----------|---|
| Nickel oxide | | 500–650 | T | 0.52–0.59 | 1 |
| Oil, lubricating | 0.025 mm film | 20 | T | 0.27 | 2 |
| Oil, lubricating | 0.050 mm film | 20 | T | 0.46 | 2 |
| Oil, lubricating | 0.125 mm film | 20 | T | 0.72 | 2 |
| Oil, lubricating | film on Ni base: Ni base only | 20 | T | 0.05 | 2 |
| Oil, lubricating | thick coating | 20 | T | 0.82 | 2 |
| Paint | 8 different colors and qualities | 70 | SW | 0.88–0.96 | 9 |
| Paint | 8 different colors and qualities | 70 | LW | 0.92–0.94 | 9 |
| Paint | Aluminum, vari- ous ages | 50–100 | T | 0.27–0.67 | 1 |
| Paint | cadmium yellow | | T | 0.28–0.33 | 1 |
| Paint | chrome green | | T | 0.65–0.70 | 1 |
| Paint | cobalt blue | | T | 0.7–0.8 | 1 |
| Paint | oil | 17 | SW | 0.87 | 5 |
| Paint | oil based, aver- age of 16 colors | 100 | T | 0.94 | 2 |
| Paint | oil, black flat | 20 | SW | 0.94 | 6 |
| Paint | oil, black gloss | 20 | SW | 0.92 | 6 |
| Paint | oil, gray flat | 20 | SW | 0.97 | 6 |
| Paint | oil, gray gloss | 20 | SW | 0.96 | 6 |
| Paint | oil, various colors | 100 | T | 0.92–0.96 | 1 |
| Paint | plastic, black | 20 | SW | 0.95 | 6 |
| Paint | plastic, white | 20 | SW | 0.84 | 6 |
| Paper | 4 different colors | 70 | SW | 0.68–0.74 | 9 |
| Paper | 4 different colors | 70 | LW | 0.92–0.94 | 9 |
| Paper | black | | T | 0.90 | 1 |
| Paper | black, dull | | T | 0.94 | 1 |
| Paper | black, dull | 70 | SW | 0.86 | 9 |
| Paper | black, dull | 70 | LW | 0.89 | 9 |
| Paper | blue, dark | | T | 0.84 | 1 |
| Paper | coated with black lacquer | | T | 0.93 | 1 |
| Paper | green | | T | 0.85 | 1 |
| Paper | red | | T | 0.76 | 1 |
| Paper | white | 20 | T | 0.7–0.9 | 1 |
| Paper | white bond | 20 | T | 0.93 | 2 |
| Paper | white, 3 different glosses | 70 | SW | 0.76–0.78 | 9 |
| Paper | white, 3 different glosses | 70 | LW | 0.88–0.90 | 9 |
| Paper | yellow | | T | 0.72 | 1 |
| Plaster | | 17 | SW | 0.86 | 5 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|-----------------|--|-----------|-----|-----------|---|
| Plaster | plasterboard, untreated | 20 | SW | 0.90 | 6 |
| Plaster | rough coat | 20 | T | 0.91 | 2 |
| Plastic | glass fibre laminate (printed circ. board) | 70 | SW | 0.94 | 9 |
| Plastic | glass fibre laminate (printed circ. board) | 70 | LW | 0.91 | 9 |
| Plastic | polyurethane isolation board | 70 | LW | 0.55 | 9 |
| Plastic | polyurethane isolation board | 70 | SW | 0.29 | 9 |
| Plastic | PVC, plastic floor, dull, structured | 70 | SW | 0.94 | 9 |
| Plastic | PVC, plastic floor, dull, structured | 70 | LW | 0.93 | 9 |
| Platinum | | 100 | T | 0.05 | 4 |
| Platinum | | 1000–1500 | T | 0.14–0.18 | 1 |
| Platinum | | 1094 | T | 0.18 | 4 |
| Platinum | | 17 | T | 0.016 | 4 |
| Platinum | | 22 | T | 0.03 | 4 |
| Platinum | | 260 | T | 0.06 | 4 |
| Platinum | | 538 | T | 0.10 | 4 |
| Platinum | pure, polished | 200–600 | T | 0.05–0.10 | 1 |
| Platinum | ribbon | 900–1100 | T | 0.12–0.17 | 1 |
| Platinum | wire | 1400 | T | 0.18 | 1 |
| Platinum | wire | 500–1000 | T | 0.10–0.16 | 1 |
| Platinum | wire | 50–200 | T | 0.06–0.07 | 1 |
| Porcelain | glazed | 20 | T | 0.92 | 1 |
| Porcelain | white, shiny | | T | 0.70–0.75 | 1 |
| Rubber | hard | 20 | T | 0.95 | 1 |
| Rubber | soft, gray, rough | 20 | T | 0.95 | 1 |
| Sand | | | T | 0.60 | 1 |
| Sand | | 20 | T | 0.90 | 2 |
| Sandstone | polished | 19 | LLW | 0.909 | 8 |
| Sandstone | rough | 19 | LLW | 0.935 | 8 |
| Silver | polished | 100 | T | 0.03 | 2 |
| Silver | pure, polished | 200–600 | T | 0.02–0.03 | 1 |
| Skin | human | 32 | T | 0.98 | 2 |
| Slag | boiler | 0–100 | T | 0.97–0.93 | 1 |
| Slag | boiler | 1400–1800 | T | 0.69–0.67 | 1 |
| Slag | boiler | 200–500 | T | 0.89–0.78 | 1 |
| Slag | boiler | 600–1200 | T | 0.76–0.70 | 1 |
| Snow: See Water | | | | | |
| Soil | dry | 20 | T | 0.92 | 2 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|-----------------|--------------------------------------|-----------|----|-----------|---|
| Soil | saturated with water | 20 | T | 0.95 | 2 |
| Stainless steel | alloy, 8% Ni, 18% Cr | 500 | T | 0.35 | 1 |
| Stainless steel | rolled | 700 | T | 0.45 | 1 |
| Stainless steel | sandblasted | 700 | T | 0.70 | 1 |
| Stainless steel | sheet, polished | 70 | SW | 0.18 | 9 |
| Stainless steel | sheet, polished | 70 | LW | 0.14 | 9 |
| Stainless steel | sheet, untreated, somewhat scratched | 70 | SW | 0.30 | 9 |
| Stainless steel | sheet, untreated, somewhat scratched | 70 | LW | 0.28 | 9 |
| Stainless steel | type 18-8, buffed | 20 | T | 0.16 | 2 |
| Stainless steel | type 18-8, oxidized at 800°C | 60 | T | 0.85 | 2 |
| Stucco | rough, lime | 10–90 | T | 0.91 | 1 |
| Styrofoam | insulation | 37 | SW | 0.60 | 7 |
| Tar | | | T | 0.79–0.84 | 1 |
| Tar | paper | 20 | T | 0.91–0.93 | 1 |
| Tile | glazed | 17 | SW | 0.94 | 5 |
| Tin | burnished | 20–50 | T | 0.04–0.06 | 1 |
| Tin | tin-plated sheet iron | 100 | T | 0.07 | 2 |
| Titanium | oxidized at 540°C | 1000 | T | 0.60 | 1 |
| Titanium | oxidized at 540°C | 200 | T | 0.40 | 1 |
| Titanium | oxidized at 540°C | 500 | T | 0.50 | 1 |
| Titanium | polished | 1000 | T | 0.36 | 1 |
| Titanium | polished | 200 | T | 0.15 | 1 |
| Titanium | polished | 500 | T | 0.20 | 1 |
| Tungsten | | 1500–2200 | T | 0.24–0.31 | 1 |
| Tungsten | | 200 | T | 0.05 | 1 |
| Tungsten | | 600–1000 | T | 0.1–0.16 | 1 |
| Tungsten | filament | 3300 | T | 0.39 | 1 |
| Varnish | flat | 20 | SW | 0.93 | 6 |
| Varnish | on oak parquet floor | 70 | SW | 0.90 | 9 |
| Varnish | on oak parquet floor | 70 | LW | 0.90–0.93 | 9 |
| Wallpaper | slight pattern, light gray | 20 | SW | 0.85 | 6 |
| Wallpaper | slight pattern, red | 20 | SW | 0.90 | 6 |
| Water | distilled | 20 | T | 0.96 | 2 |
| Water | frost crystals | –10 | T | 0.98 | 2 |
| Water | ice, covered with heavy frost | 0 | T | 0.98 | 1 |
| Water | ice, smooth | 0 | T | 0.97 | 1 |

Table 6.1 T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity; 6: Reference (continued)

| 1 | 2 | 3 | 4 | 5 | 6 |
|-------|---------------------------|-----------|-----|-----------|---|
| Water | ice, smooth | –10 | T | 0.96 | 2 |
| Water | layer >0.1 mm thick | 0–100 | T | 0.95–0.98 | 1 |
| Water | snow | | T | 0.8 | 1 |
| Water | snow | –10 | T | 0.85 | 2 |
| Wood | | 17 | SW | 0.98 | 5 |
| Wood | | 19 | LLW | 0.962 | 8 |
| Wood | ground | | T | 0.5–0.7 | 1 |
| Wood | pine, 4 different samples | 70 | SW | 0.67–0.75 | 9 |
| Wood | pine, 4 different samples | 70 | LW | 0.81–0.89 | 9 |
| Wood | planed | 20 | T | 0.8–0.9 | 1 |
| Wood | planed oak | 20 | T | 0.90 | 2 |
| Wood | planed oak | 70 | SW | 0.77 | 9 |
| Wood | planed oak | 70 | LW | 0.88 | 9 |
| Wood | plywood, smooth, dry | 36 | SW | 0.82 | 7 |
| Wood | plywood, untreated | 20 | SW | 0.83 | 6 |
| Wood | white, damp | 20 | T | 0.7–0.8 | 1 |
| Zinc | oxidized at 400°C | 400 | T | 0.11 | 1 |
| Zinc | oxidized surface | 1000–1200 | T | 0.50–0.60 | 1 |
| Zinc | polished | 200–300 | T | 0.04–0.05 | 1 |
| Zinc | sheet | 50 | T | 0.20 | 1 |

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