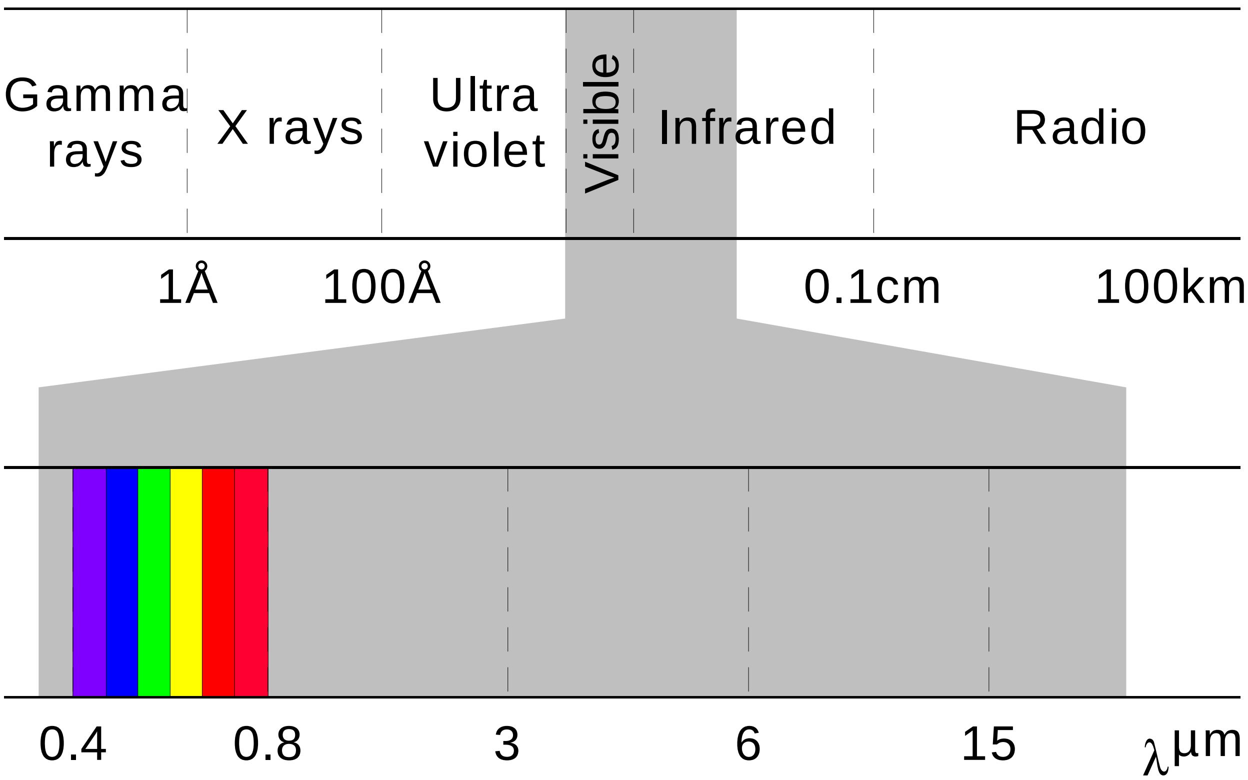
Temperature Measurement with Radiation Thermometers

Most industrial processes require the measurement of temperature. A radiation thermometer can measure the temperature of an object without physical contact. Such a system does not contaminate , damage, or interfere with the object being monitored and has many advantages over other measurement devices. The radiation thermometer can be mounted remotely from the hot target enabling it to operate for long periods of time with minimal maintenance.

Electromagnetic Spectrum

A radiation thermometer determines the temperature of an object by measuring the electromagnetic energy it emits. Any object whose temperature is above absolute zero is capable of radiating electromagnetic energy which is propagated through space at the speed of light. The electromagnetic spectrum contains many different forms of electromagnetic emissions, including infrared, light, X-rays, radio waves, and several others. The only difference between these emissions is their wavelength which is related to frequency. Radiation thermometers are designed to respond to wavelengths within the infrared portion of the spectrum. In practice temperature measurement is made using thermometers operational over many different ranges of wavelength, which generally reside somewhere between 0.2 to 20μm. The human eye is responsive to infrared emissions within the visible region of the infrared portion of the spectrum. It is this response which gives the eye its capability to observe the temperature of metal being heated in the form of a change in colour from dull red through to bright white. Most infrared emissions are outside the range of the human eye and therefore cannot be seen. They can however still be focused by an optical system on to a detector inside a radiation thermometer in a similar way to visible light.

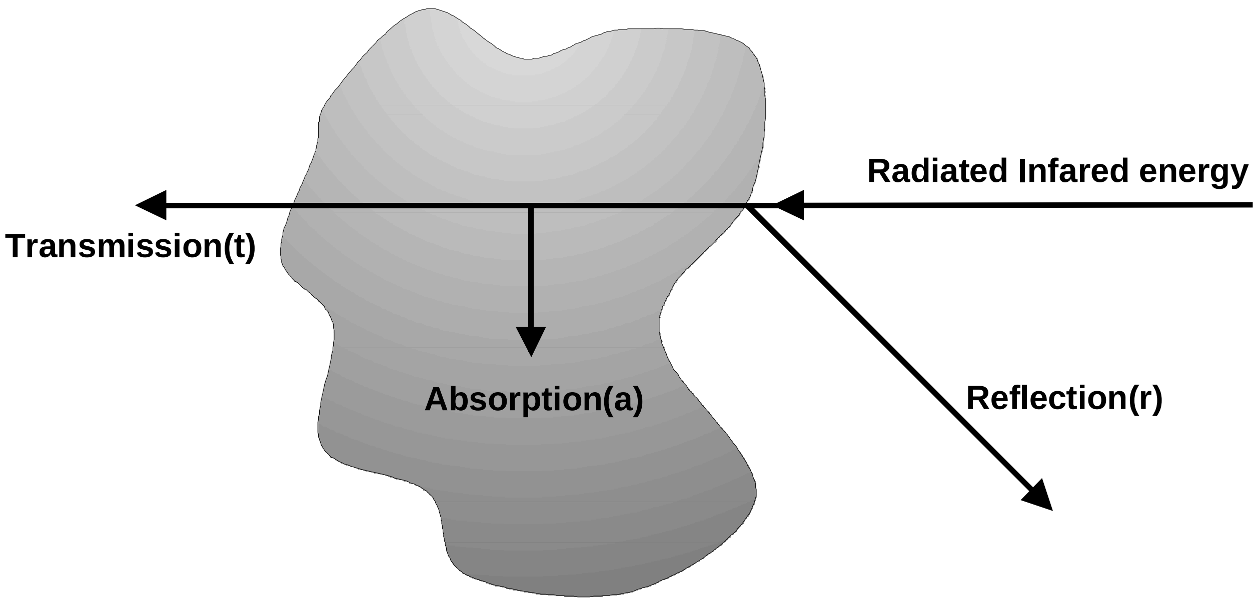


Electromagnetic Spectrum

Absorption Transmission and Reflection

When the infrared radiated by an object reaches another body, a portion of the energy received will be absorbed, a portion will be reflected and if the body is not opaque a portion will be transmitted through. The sum total of the three individual parts must always add up to the initial value of radiation which left the source.
We can say that if a, r, and t are the bodies fractional absorption, reflection and transmission respectively then:

$$a + r + t = 1.0$$



Absorption, transmission, and reflection of incident radiation by a body

If we have a body which is totally non reflective and completely opaque then all the radiated energy received by this body will be absorbed. This type of body is a perfect absorber and will also be a perfect emitter of infrared radiation. A perfect absorber and hence emitter of infrared energy is refered to as a black body. A black body would not necessary appear to be black in colour as the words black body are a technical term to describe an object capable of absorbing all radiation falling on it and emitting maximum infrared energy for a given temperature. In practice surfaces of materials are not perfect absorbers and tend to emit and reflect infrared energy. A non black body would absorb less energy than a black body under similar conditions and hence would radiate less infrared energy even though it was at the same temperature. The knowledge of a surfaces ability to radiate infrared is important when using an infrared thermometer.

Radiation Laws

The level of radiation within a body can be expressed in the mathematical formula derived by Plank.

$$J_{\lambda T} \cdot d\lambda = \frac{C1}{\lambda^5 \cdot \left[\exp\left(\frac{C2}{\lambda . T}\right) - 1\right]}$$

Where $J_{\lambda T} \cdot d\lambda$ = black body radiation emitted at temperature T (kelvin) between wavelengths λ and $d\lambda$

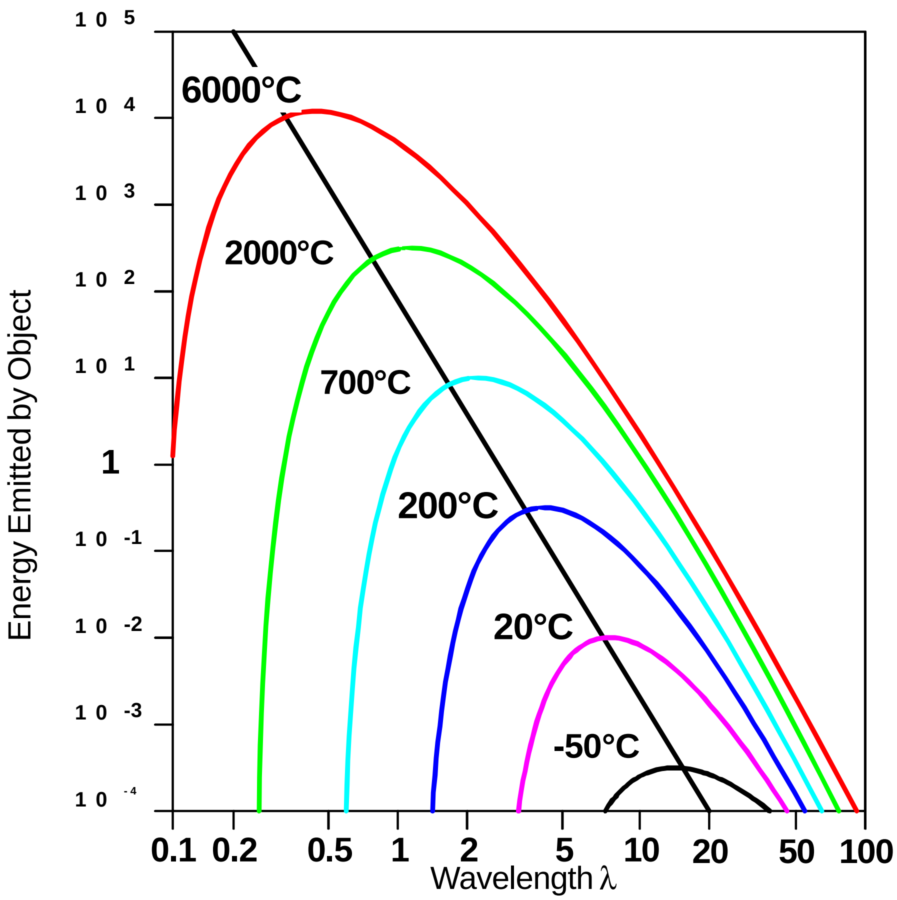
Where C1 is Planks first constant = 3.74×10^{-16} W.m^2

Where C2 is Planks second constant = 1.4388×10^{-2} m.K

Wien simplified Plank's law by ignoring the -1 to produce the following the mathematical formula.

$$J_{\lambda T} \cdot d\lambda = \frac{C1}{\lambda^5 \cdot \left[\exp\left(\frac{C2}{\lambda . T}\right)\right]}$$

The distribution of energy across a portion of the infrared spectrum is shown below. The curves in the graph have been constructed using Planks Law.



Distribution of Radiated Energy from targets at various temperatures

Observation of the curves show the following characteristics:

- As the temperature of the object is increased the curve increases in amplitude and the peak value shifts towards the shorter wavelengths.
- At wavelengths shorter than the peak the rate of rise of the curve is very fast.
- At wavelengths longer than the peak the rate of rise of the curve is quite slow and is roughly linear.

The relationship between the wavelength at which peak energy occurs for a given object temperature can be obtained by a mathematical manipulation of Plank's law. The result of this manipulation is called Wien's displacement law and is shown below.

$$\lambda_m . T = 2.898 \times 10^{-3} \text{ m.K}$$

Where λ_m is the wavelength at which maximum energy is emitted by a Black body at temperature T (Kelvin)

This formula can be useful in predicting the wavelength at which peak energy will occur for any given target temperature.

example: A target is at a temperature of 27°C. The wavelength at which maximum energy occurs for this temperature is calculated as follows:

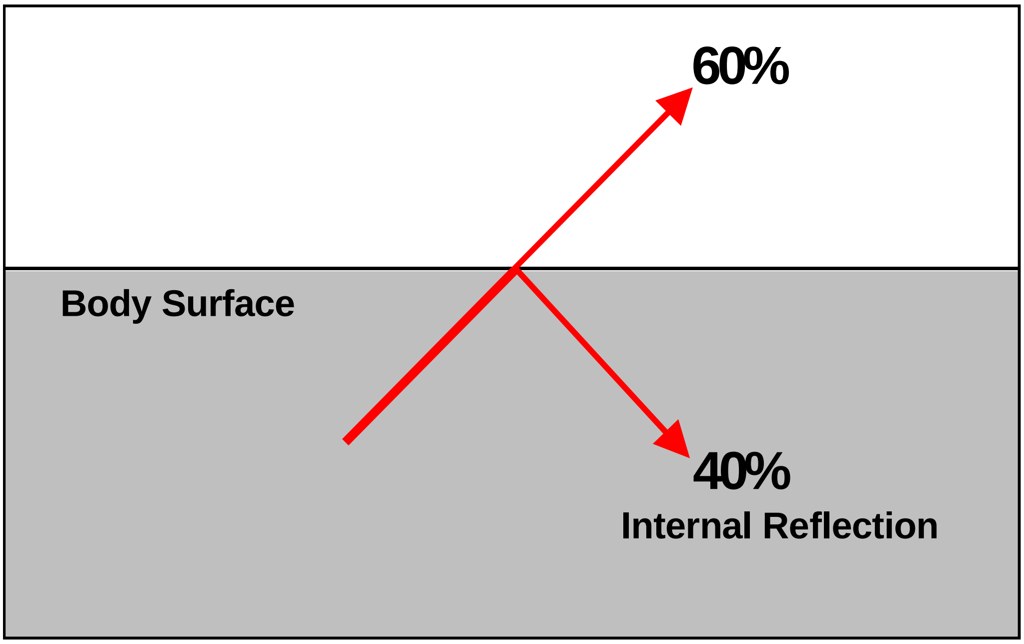
$$\lambda_m = \frac{2898}{(27 + 273)} = \text{around } 10\ \mu\text{m}$$

As can be seen for a target is at 27°C. the bulk of the radiated energy would be distributed around 10 µm.

Using a similar calculation the wavelength at which peak energy would occur for a target at 1000 ° C. would be 2.4 µm.

Emissivity

An object which radiates the maximum possible energy for its temperature is known as a Black body. Black bodies are ideal sources of infrared energy and infrared thermometers are calibrated in terms of black body radiation. In practice there are no materials which are ideal emitters of infrared and objects tend to radiate less energy than black bodies even though they may be at the same temperature.



The diagram shows why objects are not perfect emitters of infrared energy. As the energy moves towards the surface a certain amount is reflected back inside, and this internally reflected energy will never leave by radiative means. An objects ability to radiate infrared energy depends upon several factors which include, type of material, surface condition and wavelength. The value of emissivity for an object is an expression of its ability to radiate infrared energy. Emissivity is really a comparison between the energy emitted by the target object and an ideal emitter or black body at the same temperature. Hence emissivity may be expressed as follows:

$$\textbf{Emissivity} \quad \varepsilon = \frac{\textbf{Radiation Emitted by target object at Temperature (T)}}{\textbf{Radiation Emitted by a Black Body at Temperature (T)}}$$

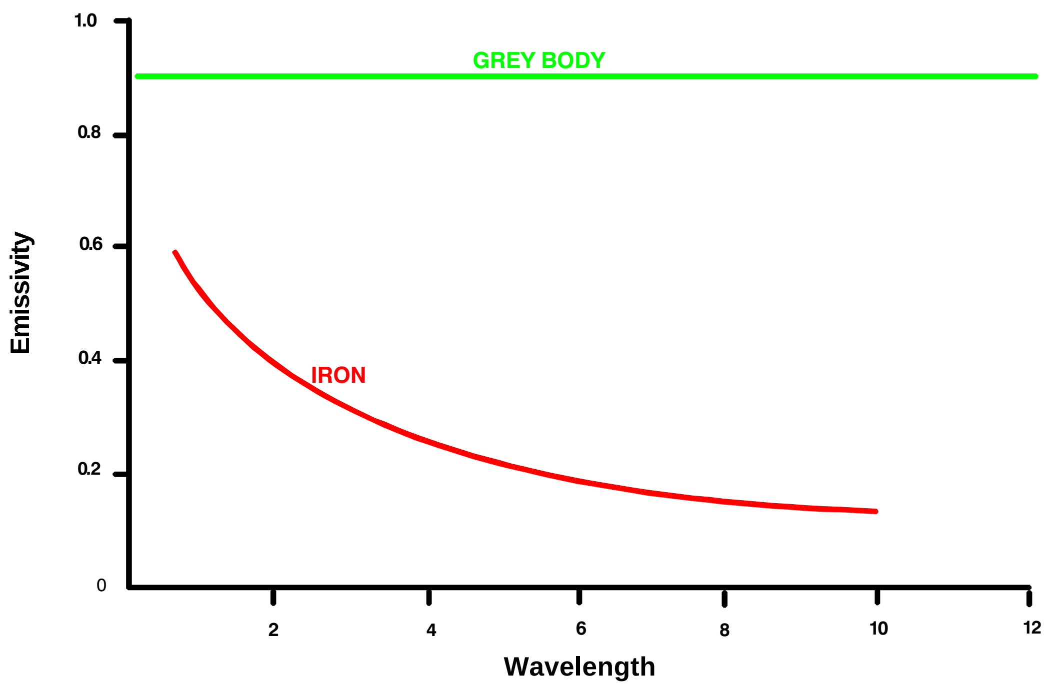
Some typical values for emissivity are shown.

Material	**Emissivity Value at 1µm**
Iron and Steel Oxidised	0.35 0.85
Aluminium Oxidised	0.13 0.40
Copper Oxidised	0.06 0.80
Brick	0.8
Asphalt	0.85
Asbestos	0.90

Observation of the above table shows the non metals such as brick tend to have high values of emissivity. Metals with unoxidised surfaces tend to have quite low emissivities. It is always worth remembering, that for an opaque object Emissivity + Reflectivity = 1.0. This means that a target surface which is quite non reflective such as asphalt would have a high emissivity, and a highly reflective material such as rolled aluminium would have a low value of emissivity. As already stated there several factors which influence the emissivity of a material. We need to be aware of them and they are as follows:

Wavelength:

The emissivity of polished metals tends to decrease as wavelength becomes longer. Non metallic materials tend to behave differently to metals often showing an increase in emissivity with increasing wavelength. Semi transparent materials such as plastic film show strong variations with wavelength and require special consideration.



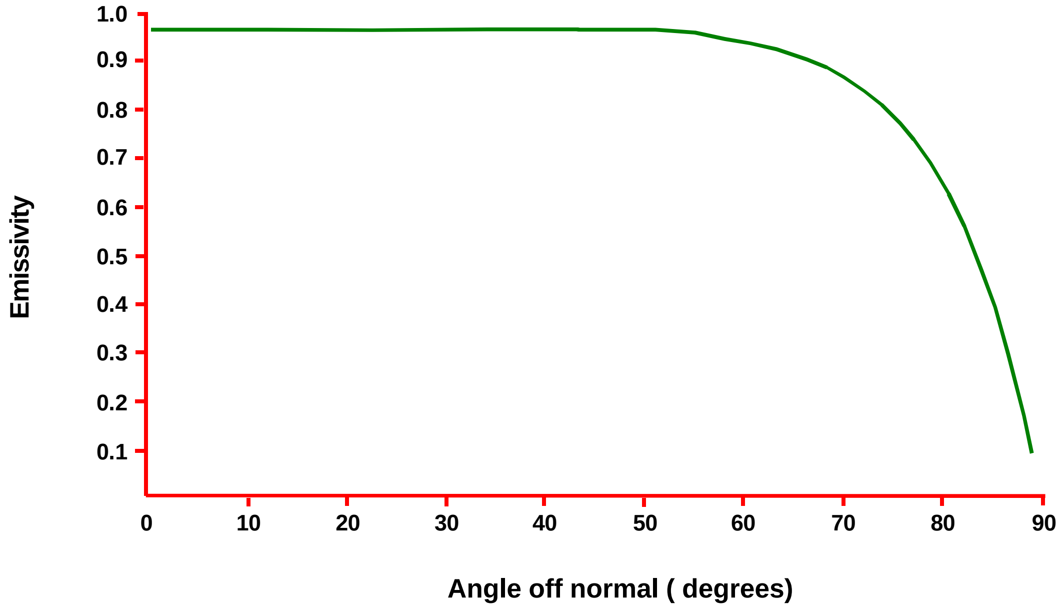
Emissivity variance with wavelength

Surface Condition:

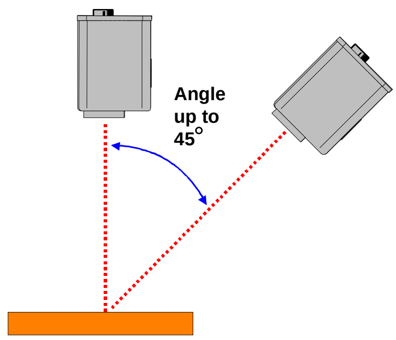
In the case of metallic materials emissivity will decrease with polishing and increase with surface roughness and the degree of oxidisation. Metals which have been subject to an industrial process e.g. rolling normally have a heavy oxide layer and have a high and stable emissivity values. Materials which have acquired a thin oxide layer such as bright metals can have an emissivity which depends critically on oxide thickness. At long wavelength the oxide layer becomes transparent and the thermometer measures the unoxidised metal surface.

Viewing Angle:

The emissivity of most materials is not strongly dependent on viewing angle provided measurement is made within about 45° of normal.



Emissivity and Angle



Maximum recommended angle for mounting thermometer

Temperature:

The emissivity of materials does not tend to change very much with temperature when using a thermometer which operates over a narrow waveband.

Emissivity Determination

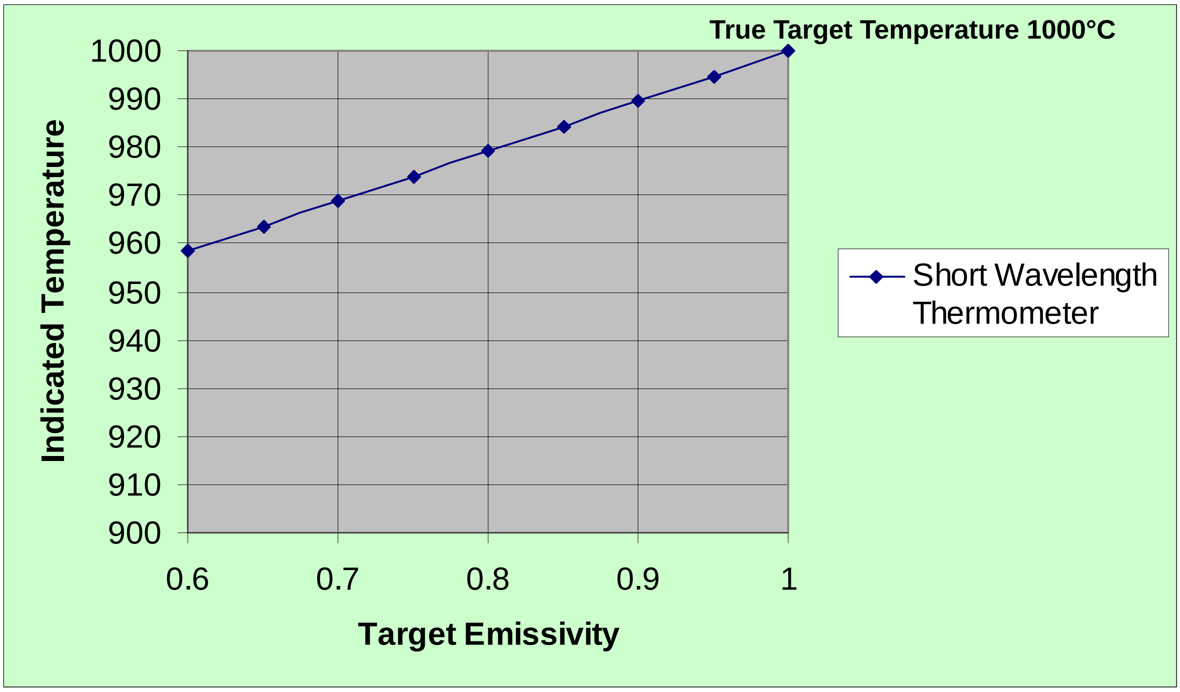
We can determine the emissivity of the surface of a target material as follows:

1. Consult the suppliers literature or operating instructions, which list typical emissivities. Caution should be used to ensure that the wavelength at which these emissivities were determined is similar to the wavelength of operation of the thermometer being used.

2. Determine the emissivity by a laboratory method. A reputable supplier of radiation thermometers will be able to supply details of this technique, and will supply a service to determine emissivity value at appropriate wavelengths.

Effect of emissivity on temperature measurement

As radiation thermometers are calibrated against black body radiation sources, they will always read incorrectly when measuring the temperature of a target with an emissivity less than 1.0. An emissivity adjustment is normally provided on the thermometer, which when set to the value of the target emissivity compensates for the non black body nature of the target and enables the correct temperature to be measured. For an accurate temperature measurement to be made it is necessary to know the emissivity of the target material. This may not be a serious problem in industrial applications which are inherently repetitive and emissivity may be considered to be a fixed quantity with some uncertainty. In practice measurement using infrared methods is usually possible. It should be understood however that certain applications notably where bright lightly oxidised metals are involved that measurement solutions may be difficult or may not even be possible.



Measurement errors if emissivity compensation is not used on thermometer

Ways of correcting for emissivity

The mathematical method:

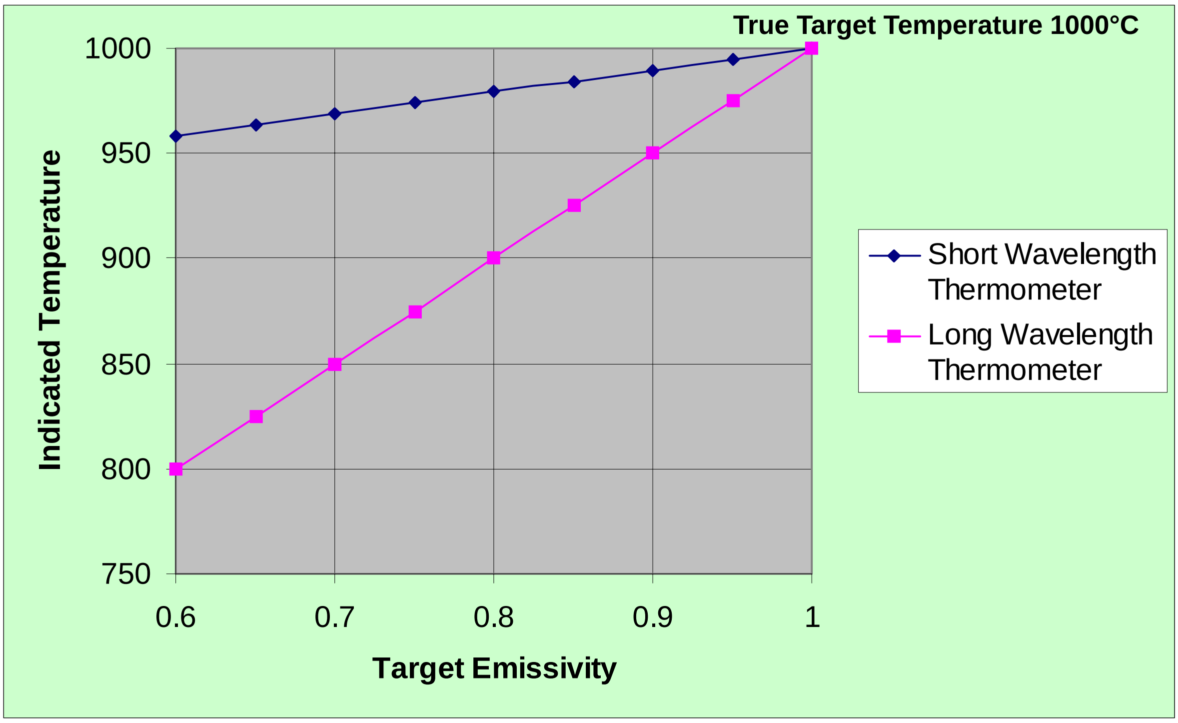
If the emissivity of the surface is known, the operator can usually set this value somewhere in the measuring system. The system uses this value as a compensation factor to eliminate the effect of the non black body target, by multiplying the thermometer output by 1/E. (E being the emissivity value of the target). For example if the target emissivity was 0.5 then the output would be multiplied by 1/0.5 = 2. Where the thermometer output undergoes signal treatment such as linearising etc, the thermometer output is multiplied electronically by 1/E before other signal treatment.

Coping with emissivity

We can adopt one of several possible approaches which can help minimise emissivity uncertainty.

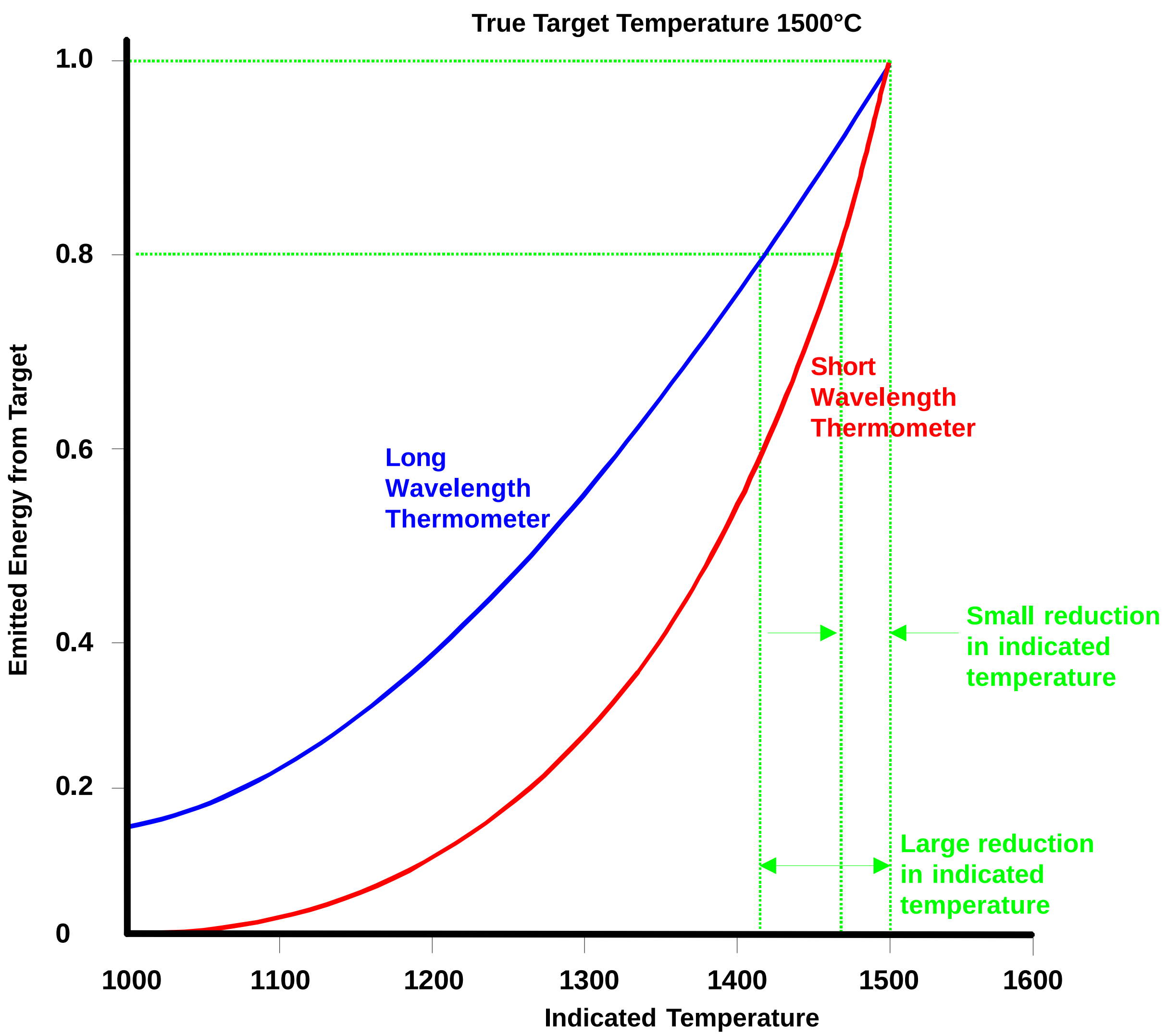
Use the shortest possible wavelength thermometer:

The energy emitted by a hot target changes very rapidly at short wavelengths, but more slowly at long wavelength. As a result thermometers which operate at short wavelength minimise the errors which occur with change in target emissivity. The diagram below shows a comparison between the errors expected from a short wavelength thermometer and one which operates at long wavelength with changes in target emissivity.



Measurement errors due to emissivity change with short and long wavelength thermometers

As can be seen the error from the short wavelength thermometer is about 10°C for a change in emissivity of about 10% at a target temperature of 1000°C. The long wavelength thermometer gives much greater errors with similar changes in target emissivity.



Comparison between short and long wavelength thermometers
to a reduction in signal

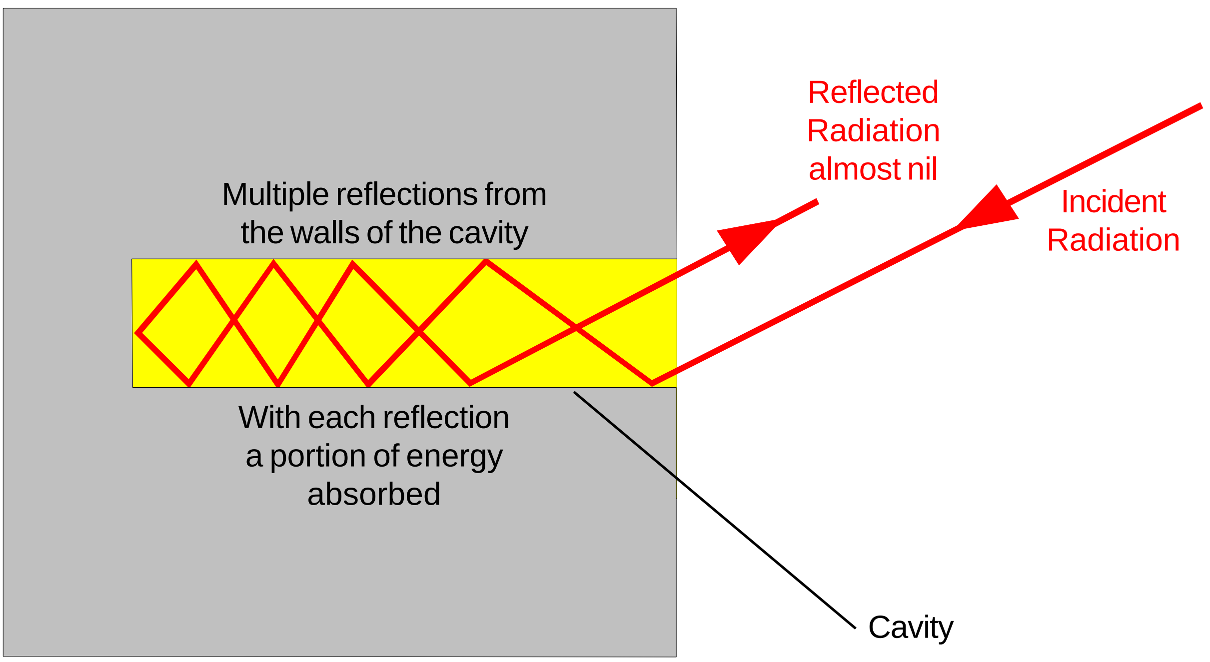
Another illustration of the improved performance of short wavelength thermometers over long wavelength thermometers is shown above. The response of both thermometers is shown on the graph. As can be seen in the event of a 20% reduction in energy from the target the reduction in indicated temperature or error from the short wavelength thermometer is about 20°C. The long wavelength thermometer gives a reduction in indicated temperature of about 80°C for a similar change in target energy.
The graph shows the rapid rise in radiated energy with temperature at short wavelength. The actual change in signal output from a short wavelength thermometer, when viewing a target at 1000°C. is often around 1 % for every 1°C change in target temperature. The result of this is that a 1% reduction in radiated energy due to say a change in target emissivity will result in a fall in indicated temperature of only 1°C. This translates to an 0.1% error in temperature.
It is often a good solution to fit a thermometer with the shortest possible vavelength which gives the benefit of minimising the errors which will occur with changes in target emissivity.
Some care must be taken when selecting a thermometer as short wavelength thermometers are not suitable for all applications. An example of this may be say measuring the temperature of semitransparent targets such as plastic film or flat glass.

Painting the surface of the target:

It may be possible to coat an area of the surface of a target with a paint which has a high and constant emissivity. Paints are available which have an emissivity of 0.9 and temperature resistance up to about 700°C. The emissivity of the coated area would appear to a thermometer to be high, even if the original uncoated surface of the target was quite low.

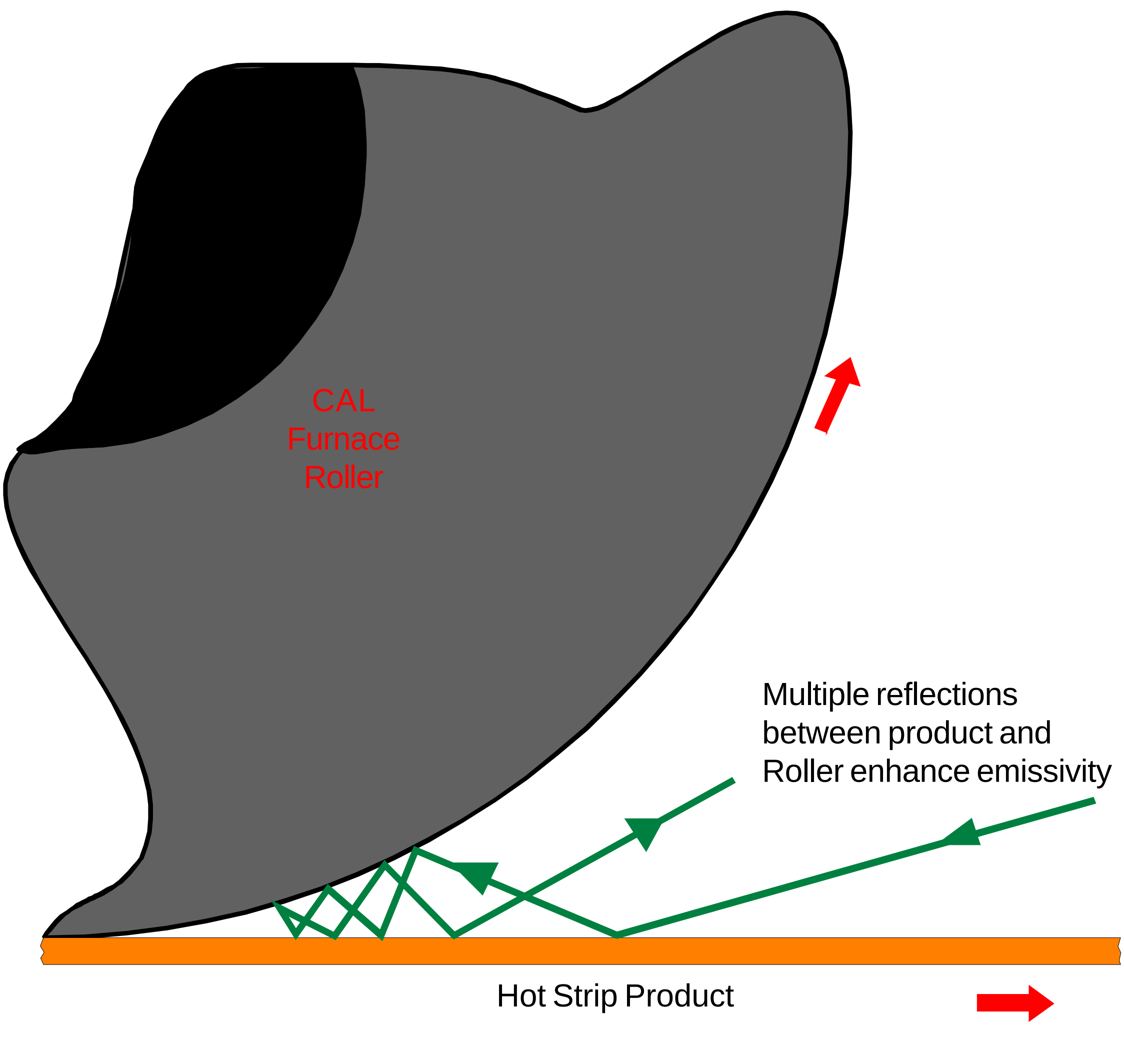
Cavities:

As already stated emissivity + reflectivity = 1.0 . When incident radiation reaches an opaque flat object a portion will be absorbed and a portion will be be reflected. The amounts of fractional absoption and reflection detemine the emissivity of the object. If reflectivity = 0 then the emissivity = 1.0 and the object can be said to be a black body.
A cavity that is at least six times deeper than its width will appear to a radiation thermometer to be almost a black body. The diagram below shows incident radiation entering the cavity. Any incident radiation entering the cavity must either be absorbed or reflected by the walls of the cavity. At each reflection, a portion of the energy is absorbed. After multiple reflections the remaining energy which is finally reflected from the cavity is very small. If the reflected incident radiation is very small then the emitted energy and hence emissivity must be very high, typically 0.99. The concept of a black body cavity is fundamental when constructing a reference source for calibrating infrared thermometers.



A Black Body Cavity

Natural cavities in products or between process and product can be exploited to solve the problems of low and variable emissivity. The diagram shows an interesting example of this where a thermometer has been sighted to look into the cavity formed between the roller and hot product in a Continuous Annealing Furnace. One of the advantages of this measurement technique is that the problem of low and possibly variable product emissivity is overcome.



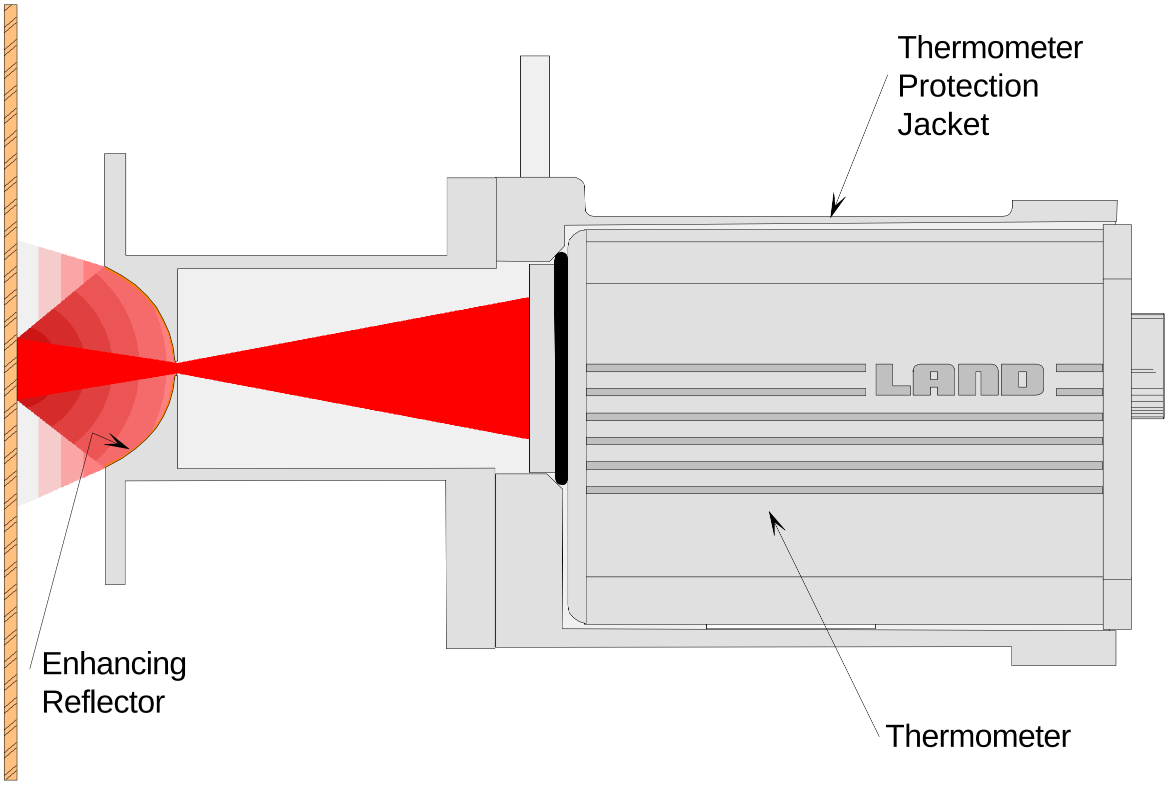
Overcoming low product emissivity on the Continuous Annealing Furnace

Emissivity Enhancers:

Based on the principles above, when a concave reflector is placed on the surface of a target its emissivity will be increased. The Land Surface Pyrometer has a detector looking into a gold plated hemisphere, which is mounted on the end of a telescopic arm. Once placed on the surface of a material the emissivity will rise to a value of about 0.95. Since the instrument is a contact device it can only be used for intermittent spot readings to prevent overheating.

Another interesting device, is the Land Emissivity Enhancer. This device uses a non-spherical reflector and again uses the principle of emissivity enhancement by multiple reflection. The Enhancer is fitted to the protection jacket of a thermometer and has been shown to give effective emissivity values as good as the Surface Pyrometer but at distances of up to 30mm from the target surface.

This gives the possibility of continuous measurement of low emissivity materials and is ideally suited to the measurement of flat strip products such as stainless steel, copper, nickel and other traditionally difficult to measure surfaces. The application of the Enhancer however should be in clean environments to prevent contamination of the reflector surface.



The Land Emissivty Enhancer

Scale Shape

The scale shape of a radiation thermometer is the relationship between the analogue thermometer output and the temperature of the target. This relationship is usually given as a table of output versus temperature at say 10°C intervals. From these tables or by calculation from a formula it is possible to calculate the percentage change in output for a 1°C rise in target temperature. This is a very useful value which can be used to measure the amount of measurement error for a given change in target emissivity. As the scaleshapes for thermometers are non linear the value of %/°C will vary with temperature. As will be seen this value will also vary with operational wavelength of the thermometer.
Calculation of %/°C:

Formula for calculating %/°C is as follows:

$$\%/°C = 100 \times \frac{C2}{\lambda T^2}$$

where C2 is a constant of 14388
Where λ is the operational wavelength of the thermometer.
Where T is the absolute temperature of the target (kelvin).

Hence for a 1µm thermometer at 1000 Kelvin the %/°C value would be as follows:

$$100 \times \frac{14388}{1 \times 1000^2} = 1.4$$

The %/°C value may be used to calculate errors quite easily.

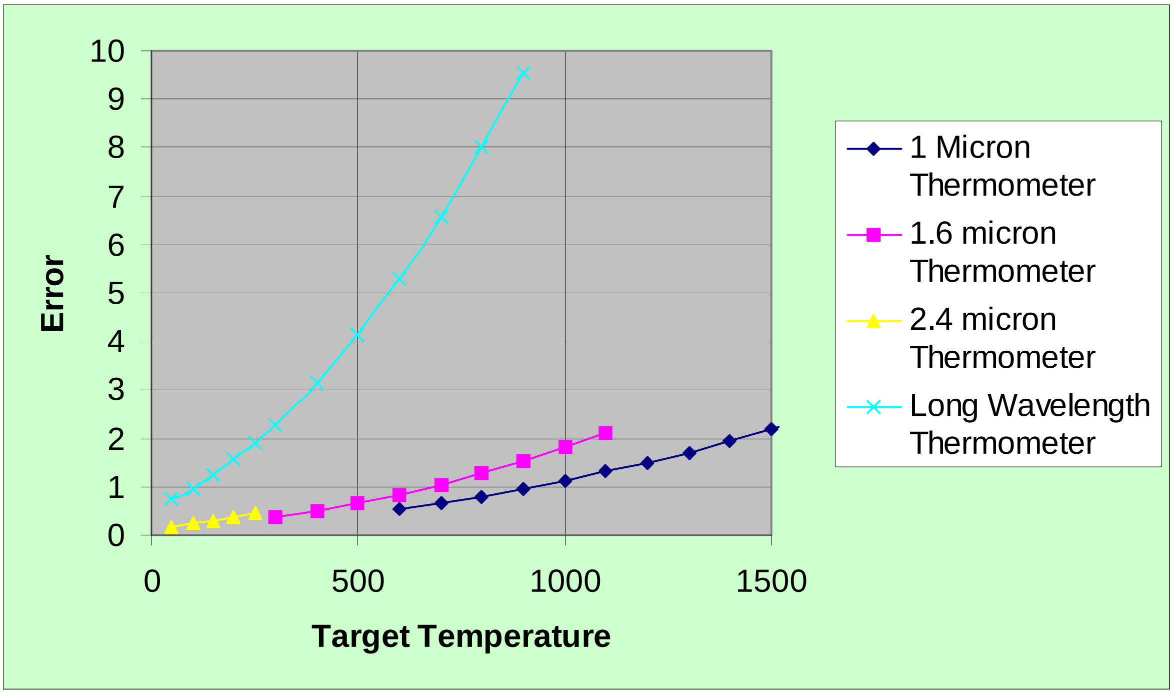
$$\text{measurement error} = \frac{\text{error in emissivity}}{\%/°C}$$

Example calculations:
For a 1µm thermometer with a %/°C value of 1.4.
If the emissivity of a target changes by +/- 5% the measurement error may be calculated as follows:
Emissivity error is +/- 5%.

measurement error is $\frac{5.0}{1.4} = +/- 3.6°C$

It should be clear that a high %/°C value reduces the effect of change in target emissivty improving the accuracy of the measurement. High values of %/°C are obtained at short wavelength and values tend to improve as the target temperature reduces.

The following chart shows expected errors in °C in the event of a 1% setting error in emissivity. Note how the shorter wavelength thermometers return smaller errors than the long wavelength thermometer.



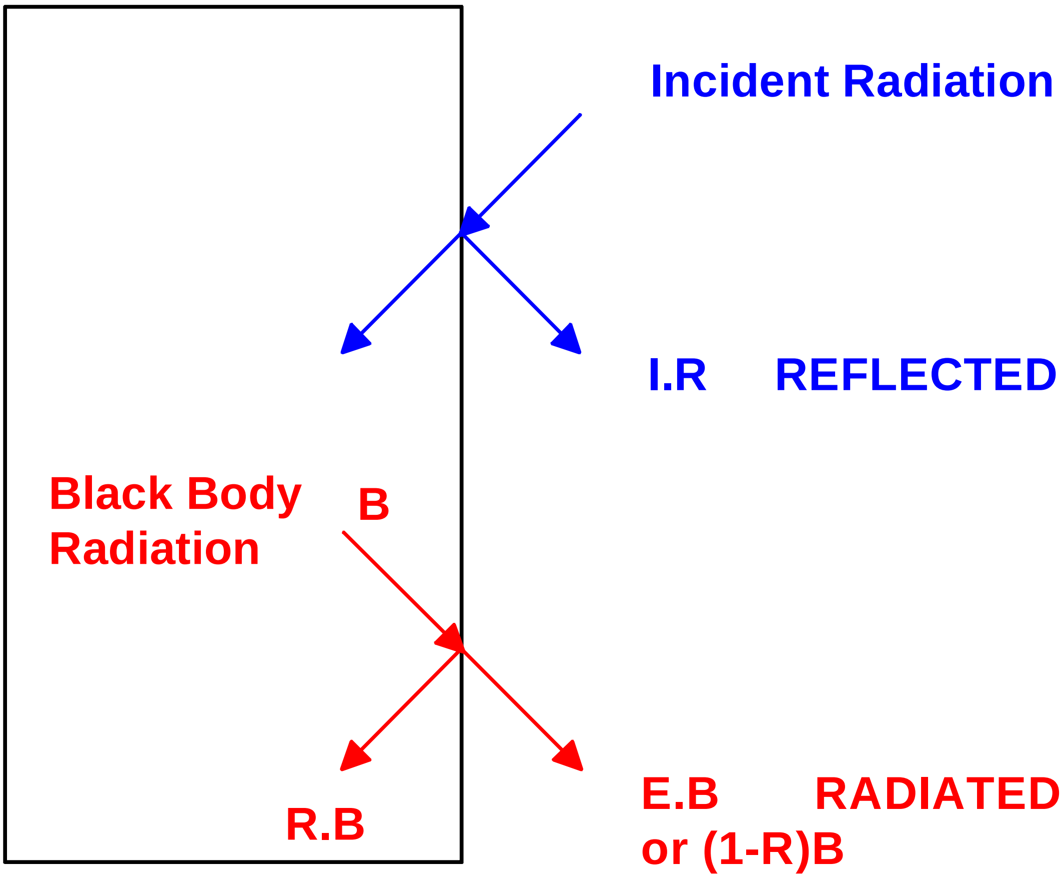
Expected measurement errors for various thermometers for a 1% error in emissivity

Reflectivity

We have seen that when radiation from the interior of a body reaches the surface it is partially reflected. The same thing happens to the radiation incident on the surface (and to the same degree).
Thus the radiation leaving the surface is the sum of the emitted radiation and that reflected. The former depends on the temperature of the body, the latter on the (average) temperature of the surroundings. The thermometer cannot distinguish between them,and the indicated temperature will therefore depend on these two temperatures as well as the reflectivity and emissivity of the surface.
We must consider three possible measurement cases:

a) A hot target in cool surroundings:

The ambient radiation is low and certainly for short wavelength thermometers can be ignored. The diagram below shows a hot target in cool surroundings. This could be for example hot product at the Roughing Stand of a Steel Rolling Mill. The output from the thermometer would be V = E.B + IR. As the surroundings are cool in comparison to the target the reflected component IR can be ignored.



Case 1 A Hot Target in Cool Surroundings

b) A hot body in surroundings at the same temperature.

Thiscould be for example measuring a target of steel in theSoaking Zone of a Steel Rolling Mill Reheat Furnace, or measurement of molten glass inside the Glass Furnace Forehearth. In this case, I = B and the radiation received is (1-R)B + R.B = B i.e. is at the black body level. This should be no surprise since the system is now a black body enclosure. No correction for emissivity is required.

c) A hot body in surroundings which are hotter than the body.

This could be for example measuring a target of steel in the Heating Zone of a Reheat Furnace. In addition to the radiated energy from the hot target there will be a large component reflected from the hot furnace walls. Large errors may now arise if no effort is made to correct for the large component of reflected radiation. This is much the most difficult case and no universal solution exists. It may be possible to screen off the ambient radiation by fitting the measuring thermometer with a water cooled sighting tube. Another method is to determine the magnetude of the reflected component and then subtract this value from the measured value to obtain true target temperature.
The following gives an example of such a system as used on a Reheat Furnace.The output of any radiation thermometer measuring stock temperature inside the reheat furnace will contain two components. One which is due to stock temperature and the second due to radiation from the hot background being reflected by the stock. This reflection problem may cause measurement errors. These can be reduced by using a two sensor system.

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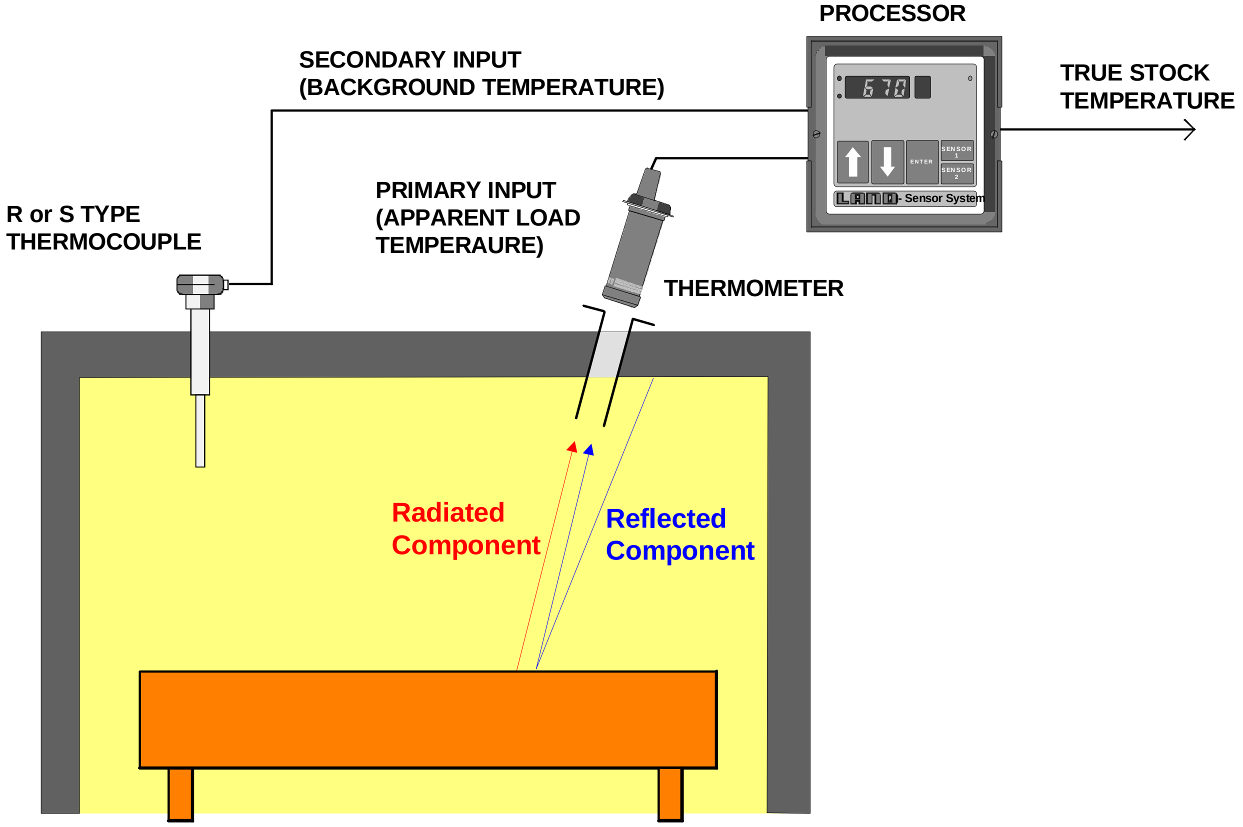
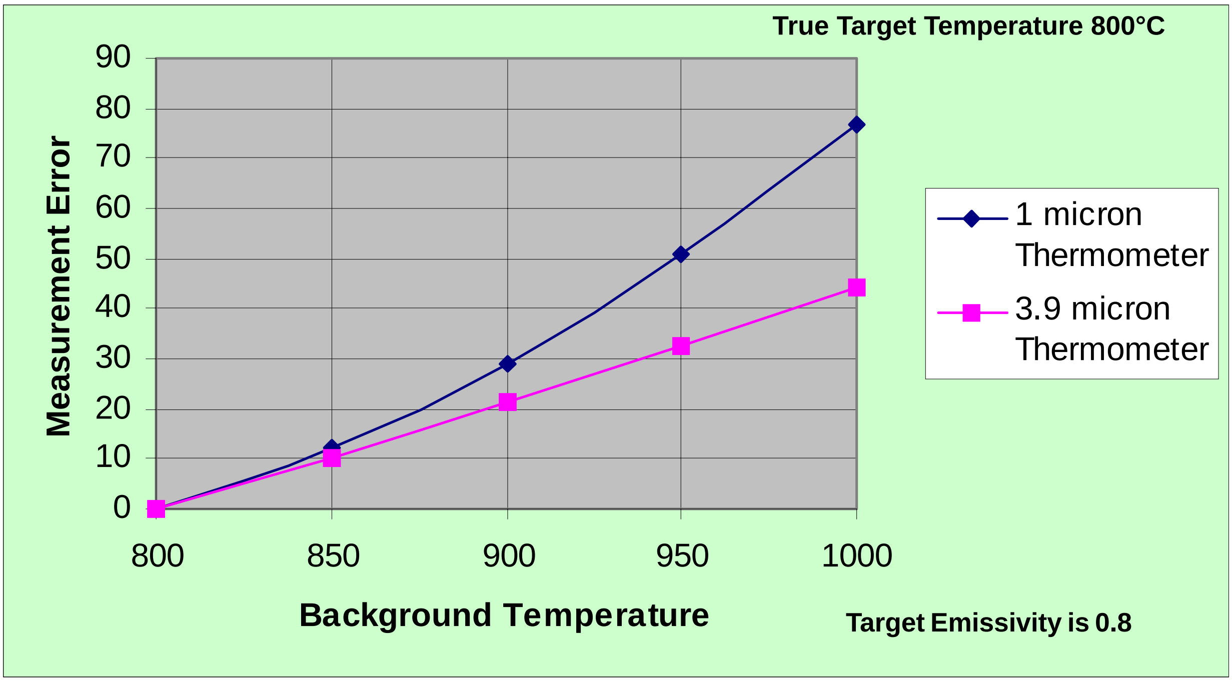


Measurement of true stock temperature using a Two Sensor System

The system thermometer is a 3.9 µm device which minimises background reflection and operates in a window where furnace gasses are transparent.
A second sensor such as a thermocouple measures background temperature. The outputs from the two sensors are fed into a processor. The processor can calculate the value of stock relectivity from the emissivity setting (r = 1-e) . With the value of reflectivity and background temperature the processor knows the magnetude of the reflection and can calculate the true load temperature corrected for background radiation.

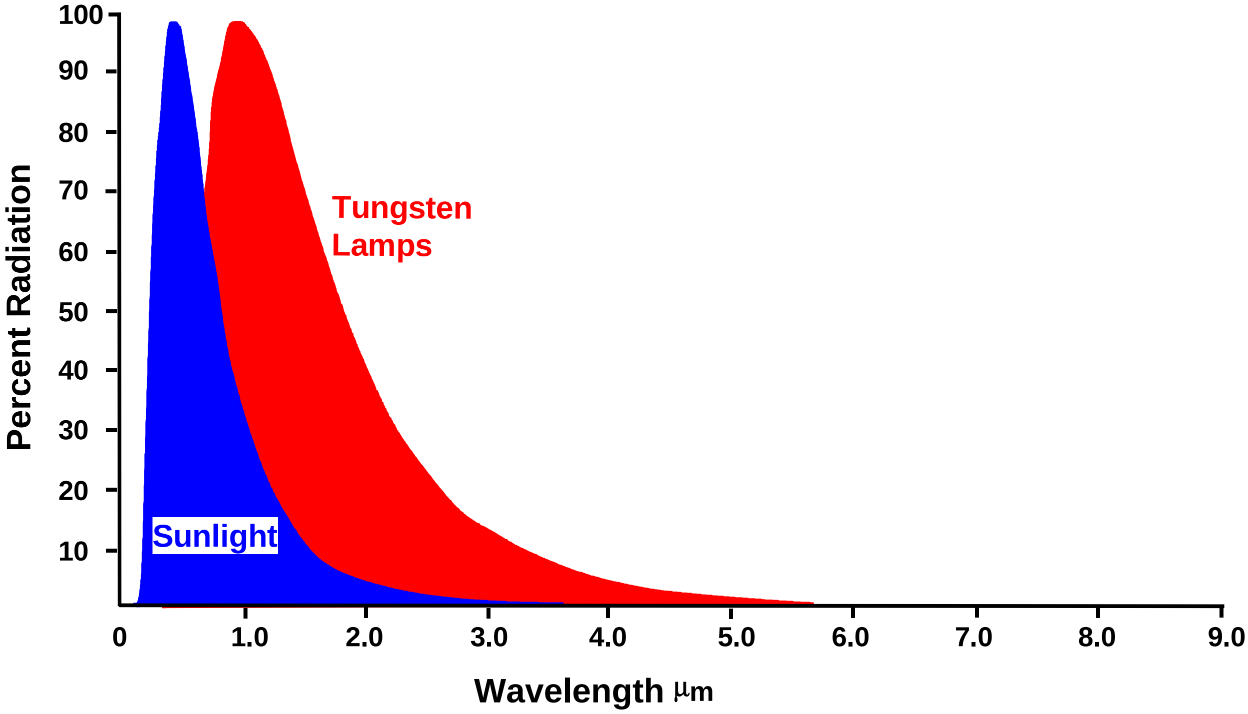


Measurement errors due to background reflection with and 1µm and 3.9µm thermometers

The graph above shows why a 3.9 µm is prefered to a short wavelength thermometer in this application. With a background or furnace wall temperature of 1000°C the 1µm thermometer would read 876°C for a true target temperature of 800°C. Under similar circumstances the 3.9µm thermometer would read 844°C. The 3.9µm thermometer is able to cope much better with reflected radiation from hot furnace walls than a shorter wavelength thermometer. It is also interesting from the graph to see that both thermometers read correctly when both background and target temperature are 800°C. Under these conditions the furnace is operating as a black body enclosure and would not require a Two Sensor System. Conditions similar to this could well occur in the Soaking Zone of the Reheat Furnace.

Other reflection problems:

Reflections from the sun or factory lighting can cause measurement problems to thermometers which operate at short wavelength. This problem can usually be overcome by the construction of a simple overhead screen to give a shaded target area. It is important to understand that it is the target spot which requires sheilding not the thermometer.



Energy distribution from Sunlight and Tungsten Lamps

Parts of a Radiation Thermometer

The essential parts of a radiation thermometer are:

(a) detector which converts the radiation incident on it into a signal, usually electrical in nature.

(b) an optical system which defines the angular field of view of the thermometer which determines the size of hot object (target size)
that is required. It may also contain a filter to select the desired band of wavelengths to which the thermometer is sensitive. The spectral sensitivity is the product of the spectral transmission of the optical system and the spectral sensitivity of the detector. Either of these may be the limiting factor.

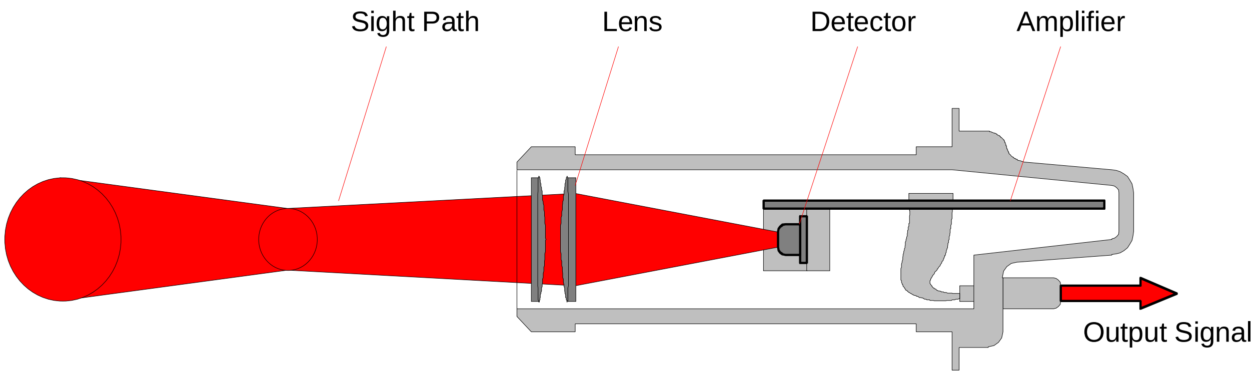
(c) a body to hold these parts

(d) an electrical connection to convey the output signal to the indicating or recording device. This is usually a demountable plug so that the thermometer can be removed easily for cleaning or checking.

There may also be

(e) a pre-amplifier which lifts the detector output from its low level (micro-amps or milli-volts) to the volts level.

(f) in portable models, direct read-out of temperature, which may be analogue or digital. Such models require a battery and often incorporate an emissivity adjustment.



Basic Components of a Radiation Thermometer

Detectors

Detectors can be split into thermal detectors and photon detectors. In thermal detectors the incident radiation is absorbed as heat, the resulting temperature rise producing the output signal. They absorb (nominally) all wavelengths, the spectral response being limited by the transmission of the optical system. Since the operation depends on the attainment of a temperature equilibrium a finite amount of radiation is required depending on the thermal mass. A fast response requires a thin (and therefore rather delicate) construction and it is not easy to build a detector with a response time of less than 100ms: many types have a response of the order of a few seconds. This is very often sufficiently fast.In photon detectors the incident photons lift electrons from the valence band into the conduction band provided that the photon has energy greater than the energy gap between these two bands: this is to say that the photon must be shorter in wavelength than a certain critical value. The resulting free electrons can be made to produce an electric current either by applying a potential across the device (photo-conductive mode) or by the presence of a p.n. junction (photovoltaic mode). The detectors used in Land thermometers work in the photo-voltaic mode. They have two important (and useful) characteristics. They operate, as indicated above, only for wavelengths below a critical wavelength so that they are essentially short wavelength devices. Since we are concerned with sub-atomic phenomena the response is extremely fast of the order of a few microseconds.

Thermal detectors include:

Thermopiles
either made from discrete elementary thermocouples,a number of these being connected in series to augment the output. The two basic metals are electron beam welded and rolled into a strip about 30 mm wide and 0.008 mm thick. The response time of such a device is of the order of 2 seconds. Faster response can only be obtained by using thinner material which is not feasible since it becomes too delicate to handle. The strips are blackened before use to improve absorption of' radiation or by deposition from the vapour phase when a much thinner material can be formed. This can give response times of the order of 0.1 second.

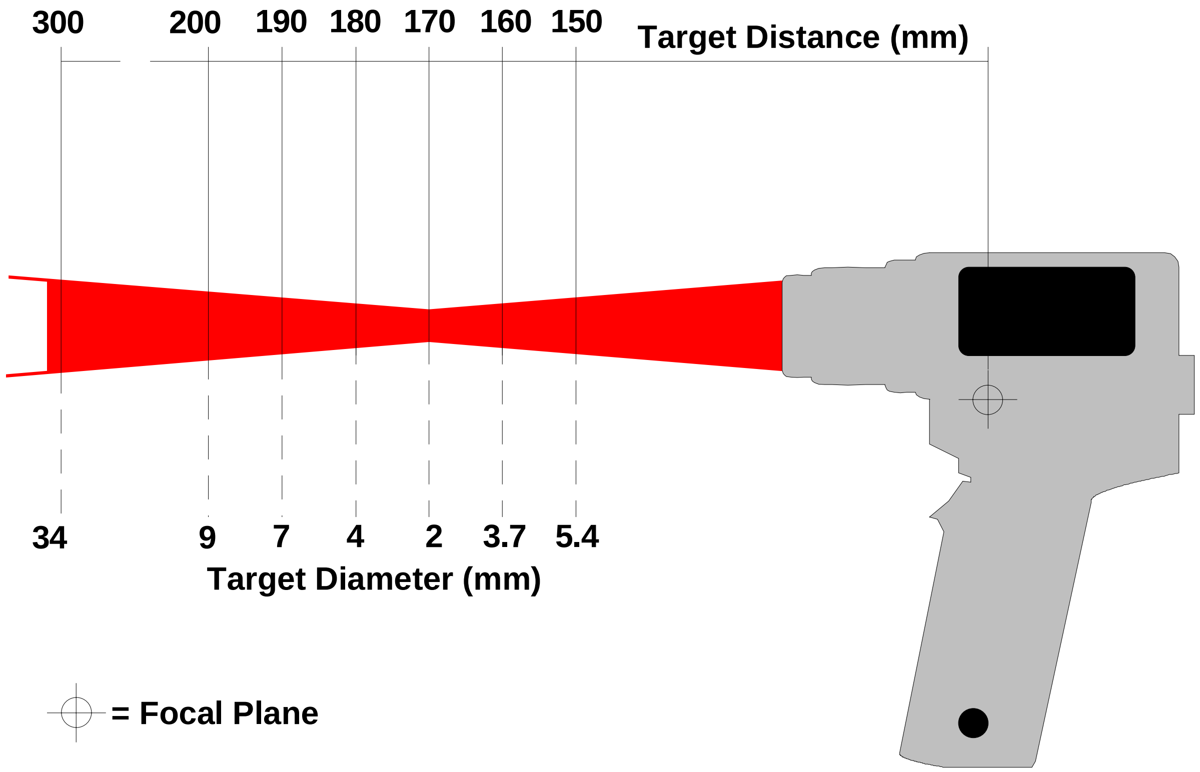
Pyro-electric
consist of a strip of material which, when heated by the incoming radiation, produces a charge between the two faces (in a manner somewhat analogous to the piezoelectric effect). By chopping the radiation an alternating voltage can be produced which is proportional to the temperature rise and hence the incoming radiation.

Photon detectors include

Silicon	spectral response 0.5 to 1.1µm
Germanium	spectral response 0.5 to 1.8µm
Lead sulphide	spectral response 0.5 to 2.8µm

Optical System

The optical system of a Land radiation thermometer comprises a lens, often with a second auxilliary lens or window in front of it; an aperture stop to restrict the effective area of the lens used, and a field stop placed in front of the detector. The essential purpose of using lenses rather than simple apertures is the resultant ability of radiation thermometer to look at smaller targets.
The radiation thermometer looks out within a precisely defined angle, collecting radiation from a cone of vision or field of view. The target spot whose temperature is to be measured is the intersectionof the field of view with the targe surface. It is very important to ensure the target is large enough to completely fill the field of view otherwise the average temperature of the target and the area of the background which can be seen by the thermometer will be returned.



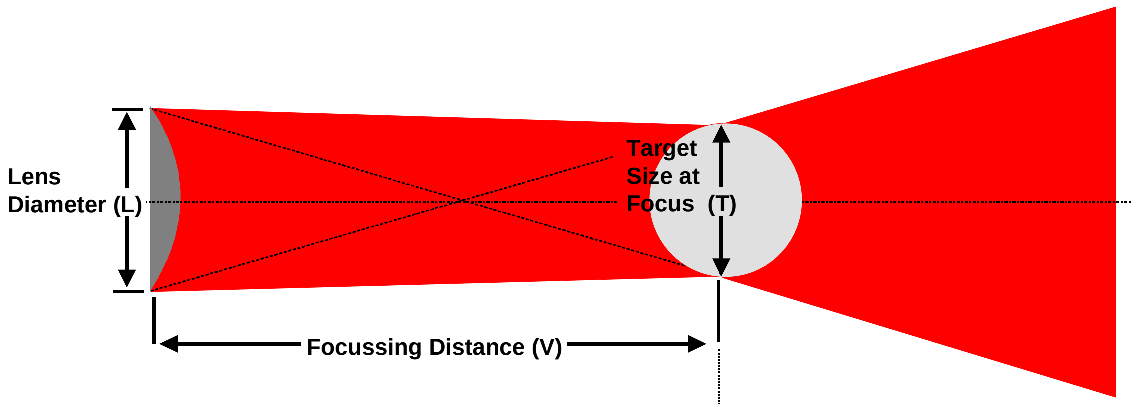
Thermometer field of vision and target sizes at distances from the datum

The above diagram shows thermometer and its field of view. The diagram shows the sizes of target required at various distances from the optical datum. The instrument focus is at 170mm from the datum. A target size of at least 2mm is required here to ensure the field of view is completely filled. The instrument may be used to measure a target at say 200mm, provided it is at least 9mm in diameter to ensure the field of view is filled.
The nominal field of view for a thermometer is set by the distance between the field stop and the optical centre of the lens divided by the field stop aperture size. The field of view can be expressed in terms of an angle or in terms of a ratio between a specified focus distance and the target size at focus. This means that if a thermometer has a quoted F.O.V of 100:1 and is focused at 1000mm, the target size at focus will be 1000 / 100 = 10mm.
Manufacturers of infrared thermometers will usually provide a table of target size values at various distances from the optical datum on the instrument.

This enables the user to ensure that the target is big enough to fill the field of view at the location of the target. The reader should be aware that the use of lenses involves the calculation of correction factors to overcome spherical (due to the shape of the lens), and chromatic aberations (due to the different wavelengths of energy passing through the lens). These factors have already been taken into account in the production of target size tables for Land thermometers. These target size tables show the minimum size of target required at a range of distances. In some instances the target size may have to be calculated for distances not shown on that table. Note that a thermometer may be stated as focusing at 1200mm, but it can be used at any distance, provided the target is sufficiently large, and there is nothing between the thermometer and the target to reduce the incident energy.
To calculate the target size at any distance you need to know just 3 factors:

a) the active lens diameter (L) of the thermometer
b) the focusing distance (V) of the thermometer
c) the target size (T) at the focusing distance

V can be obtained from the thermometer description or from the target size table, and T which is the target size at focus can also be obtained from the target size table.
L can be obtained from the target size table at zero distance.
To calculate the target size at a distance D from the thermometer use the following:



Up to Focus

Target size = $\frac{(T-L)}{V}.D + L$

Away from Focus

Target size = $\frac{(T+L)}{V}.D - L$

Note: D is distance from optical datum on thermometer to target.

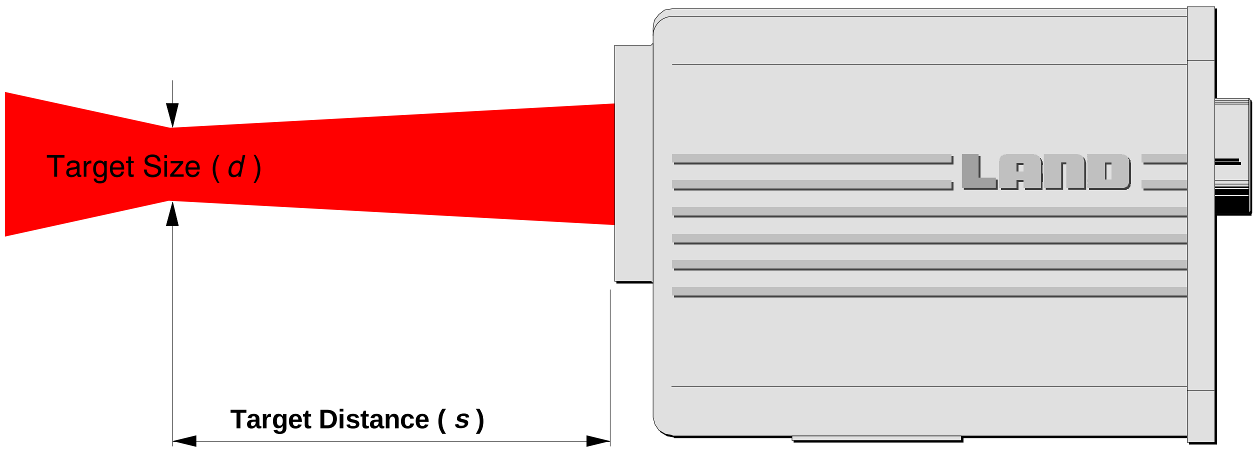
Calculation of target sizes for a fixed focus thermometer

Example: A thermometer has a lens diameter of 35mm, is focused at 600mm and has a target size at focus of 30mm. What would be the target size at 1200mm ?

target size = (30 + 35) / 600 . 1200 - 35 = 95mm.

Target size at 1200mm is therefore 95mm

The diagram below shows a thermometer which has adjustable focus and a visual sighting system. The adjustment for focus is at the rear of the unit so that it may be adjusted whilst installed in its final location. The instument is focused until a sharp image of the target is produced. A graticule in the viewfinder enables the thermometer to be sighted correctly and also indicates the required target size. The internal focusing mechanism, ensures that the visual focus and the infrared focus are simultaneously adjusted. This means that when the an adjustment is made to the visual image the infrared thermometer is also focused on the same target.



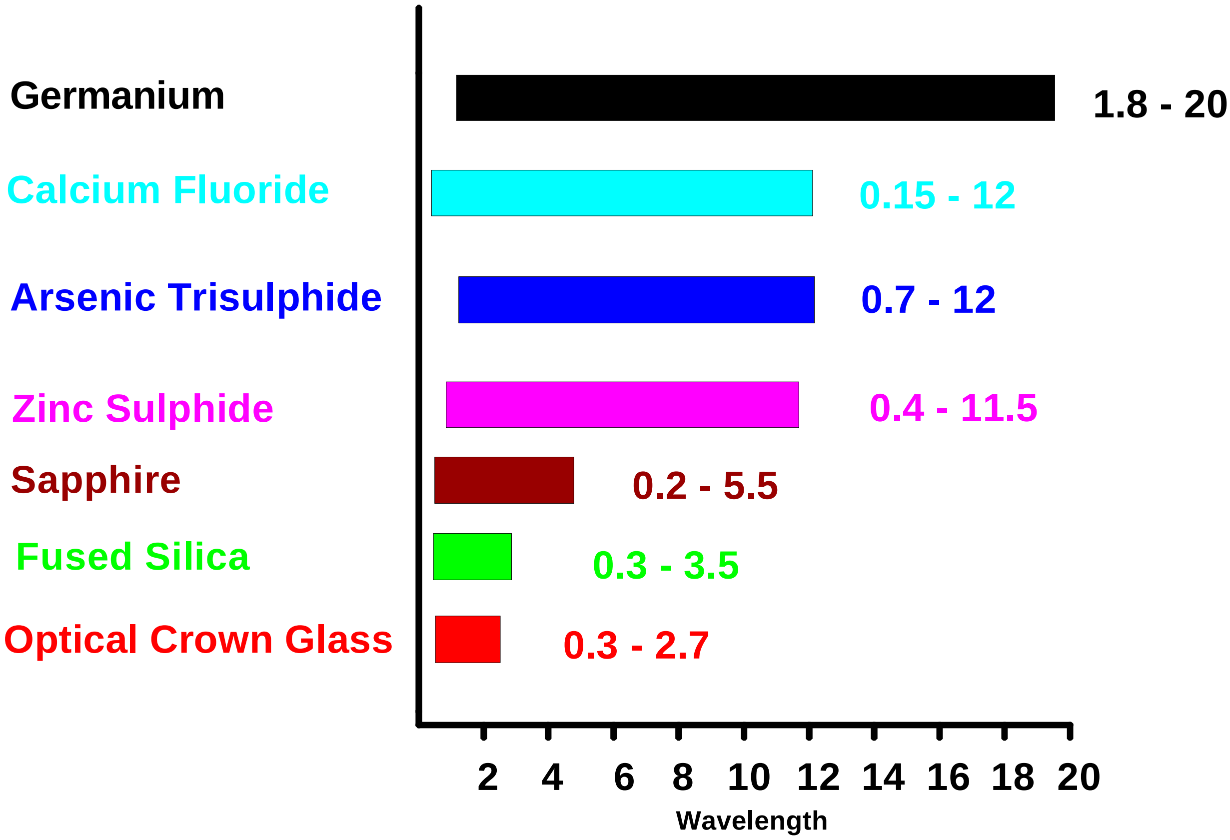
$$\text{Target Size } (d) = \frac{\text{Target distance } (s)}{\text{FOV}}$$

Calculation of target sizes for a focusable thermometer

The above instrument has a standard focus adjustment range of 500mm to infinity. This adjustment range may be modified by fitting one of a number of available auxiliary lenses to the front of the optical system. This will enable the measurement of smaller targets at distances closer than 500mm. As the instrument is focusable, the target size may easily be calculated by dividing the distance between the thermometer and target by the specified field of view.

Optical Materials

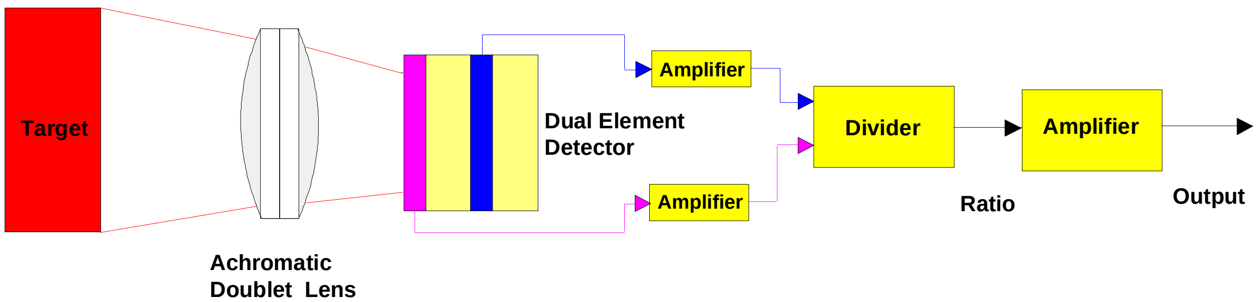
The thermometer optical system must be designed to be capable of transmitting the entire range of wavelengths within the specified spectral response. If for example a thermometer has a spectral response of 8 to 11.5 µm the optical system must be able to transmit this range of wavelengths. If the optical components of this instrument were made say of crown glass, then the thermometer would not be able to see the target correctly. The following diagram is a list of optical materials along with their transmission range.



Transmission range of materials used in infrared thermometers

Ratio Thermometers

Most infrared thermometers are single channel devices.This means that the energy from the target is focused on to one single detector.These Thermometers need to be able to see a full target. If the target is under the specified size then the Thermometer will also see some of the background and will tend to indicate a temperature somewhere between the target and background temperature.The Thermometer can only measure what it sees. Smoke steam and solid objects in the sight path will reduce the amount of infrared energy reaching the Thermometer causing it to read low.The Ratio Thermometer was developed with the intention of eliminating some of the problems of making temperature measurements with single channel instruments.
The Ratio Thermometer is a dual channel device.The optical system focuses the energy on to a dual element detector.The detectors outputs are amplified and electronically divided to produce a ratio signal which is a function of target temperature.
If the energy to a Ratio Thermometer is reduced due to obstructions in the line of sight or targets that do not fill the field of view, then both detectors are effected equally and the ratio signal remains unchanged.



The Ratio Thermometer

In practice only a small percentage of the field of view needs to be filled when using a Ratio Thermometer making it extremely useful when making temperature measurements of targets in very dusty environments.

Emissivity and Non Greyness:
For a single wavelength thermometer it is necessary to predict the value of target emissivity to obtain the correct value of target temperature. With the Ratio thermometer there are two channels which operate at different wavelengths and as a result there are two values of emissivity to consider as follows.

THERMOMETER OUTPUTS

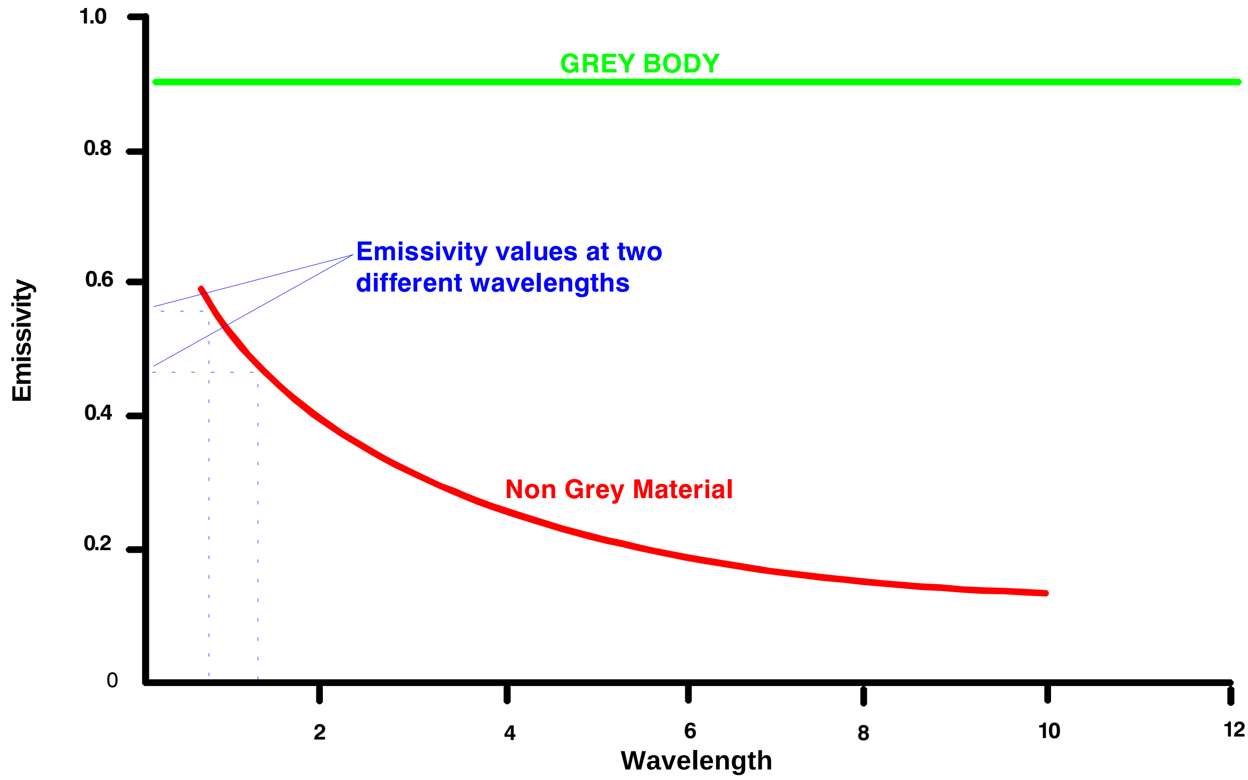
Single Wavelength Thermometer

$$\text{output} = \varepsilon . F\ Tt$$

Dual Wavelength Thermometer

$$\text{Ratio Output} = \frac{\varepsilon\lambda_1\ F\ Tt}{\varepsilon\lambda_2\ F\ Tt}$$

A material who's emissivity remains constant with wavelength is known as a greybody. It can be seen from the above formula that if a Ratio thermometer were viewing a target which is a greybody (both emissivity values exactly the same at each wavelength) then the two emissivity values would cancel and the temperature could be determined with no emissivity factor involved.
In practice emissivities of material surfaces are rarely the same at two different wavelengths and the actual ratio of the emissivities at both wavelengths is refered to as the non greyness value.



Emissivity values at two wavelengths

As the ratio thermometer sees two different emissivity values, one channel detector tends to see more energy than the other and this results in a measurement error. The non greyness control on the Ratio thermometer can be adjusted to match the ratio of the emissivities at both wavelengths or non greyness value of the target. This is similar to adjusting the emissivity value on a single wavelength thermometer, and has the effect of removing the measurement error at that particular value of target non greyness. If the emissivities of the target change equally then there will be no measurement error.
In practice however the relationship between the emissivities at both wavelengths does not remain constant and even a small change in non greyness can cause a large measurement error.

Evaluation of errors due to a change in non greyness:

A way of actually evaluating the errors of a Ratio thermometer in the event of a change in non greyness is to use the % / °C calculation as seen earlier. To do this we must obtain a % /°C value for the ratio thermometer at the temperature of interest.
It can be shown mathematically that the effective wavelength for a typical Ratio thermometer operating at say 0.95µm and 1.05µm would be about 10µm.

The effective wavelength is evaluated from the formula: $$\frac{\lambda 1.\lambda 2}{\lambda 1 - \lambda 2}$$

Where $\lambda 1$ and $\lambda 2$ are the wavelengths of the Ratio thermometer.
Once we have the effective wavelength we can again calculate the %/°C value for a target temperature of say 1000 kelvin.

$$100\text{x} \quad \frac{14388}{10\text{x}1000^{2}} = 0.14$$

The %/°C value may be used to calculate errors quite easily.

$$\text{measurement error} = \frac{\text{error in emissivity or non greyness}}{\%/°\text{C}}$$

Example calculations:

For a Ratio thermometer with a %/°C value of 0.14.
If the non greyness value of target is 1.115 and the non greyness setting on the instrument is 1.150 the measurement error may be calculated as follows:
Non greyness error is - 3%

$$\text{Measurement error is} \quad \frac{-3.0}{0.14} = -21.4°\text{C}$$

It is now interesting to compare the above result with a 1µm thermometer measuring the temperature of a target at 1000 kelvin.
A 1µm thermometer at this temperature will have a %/°C value of 1.4.
If the emissivity of a target is 0.77 and the emissivity setting on the instrument is 0.8 the measurement error may be calculated as follows:
Emissivity error is - 3%.

$$\text{measurement error is} \quad \frac{-3.0}{1.4} = -2.1°\text{C}$$

It can be clearly seen that even a small change in non greyness can cause a large error. It is often said that the setting on the non greyness control of a Ratio thermometer has to be a factor of about 10 times more precise than the emissivity on a single wavelength device to obtain similar measurement accuracy. Even if the non greyness value were set exactly right it would take only a small change in target non greyness to create quite a large measurement error. As has been mentioned, short wavelength thermometers with their high values of %/°C are very good at minimising the effect of changes in target emissivity.
Ratio thermometers do have their uses where the target does not fill the field of view or where there are obstructions in the sight path. Cement Kiln burning zones and wire rod mills are examples of this.

Windows

In some industrial applications there will be a window or viewing port between the thermometer and the target which can reduce the radiant energy reaching the thermometer. A useful statement is that “A THERMOMETER CAN ONLY MEASURE WHAT IT SEES”. The following table is a list of optical materials along with their reflection loss per surface. When using a thermometer to look through a window at a target, it is important to ensure that the operational wavelength of the thermometer falls within the useable transmission band of the window. It is also important that the loss of energy across the window and target emissivity are compensated to enable the thermometer to read the correct target temperature.

Optical Material	Usable Transmission band μm	Approximate reflection loss per surface
Optical Crown Glass	0.3 to 2.7	4%
Fused Silica	0.3 to 3.5	3.5%
Calcium Fluoride	0.15 to 12.0	3%
Germanium	1.8 to 20	3 to 36%
Sapphire	0.2 to 5.5	7%
Zinc Sulphide (cleartran)	0.4 to 11.5	15%

Transmission range and losses per surface of optical materials

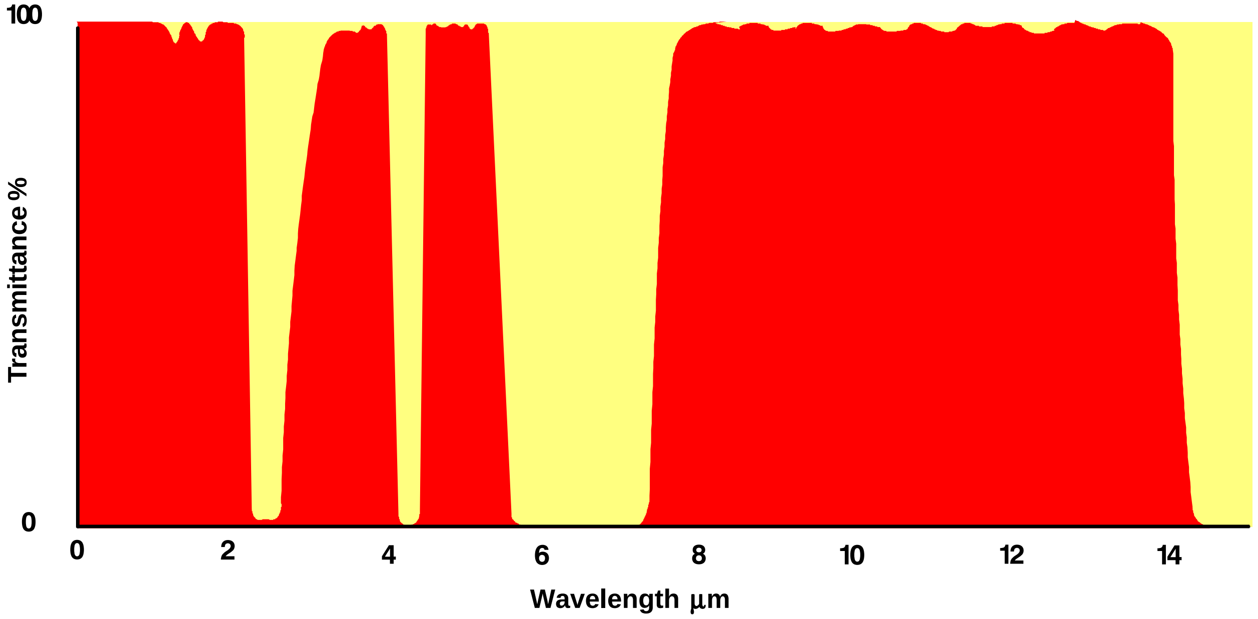
The emissivity control on the thermometer or processor can be set to compensate for target emissivity and window losses. A simple calculation provides the correct setting, as follows:
For example:- if viewing a target of emissivity 0.8 through a sapphire window the effective emissivity setting should be the product of the surface emissivity and the transmission of the sapphire. Transmission is 100% minus the reflection loss of each surface (7% + 7%) = 86% or 0.86. This value should then be multiplied by the value of target emissivity. Hence emissivity setting = 0.86 x 0.80 = 0.69

Emissivity setting = Target emissivity x 1 - (losses) / 100

Transmission Path

As has been stated, a radiation thermometer can only measure what it sees. Smoke, steam and solid objects in the sight path of the thermometer will reduce the infrared energy from the target and should be avoided wherever possible.

The diagram below shows transmission of infrared through the atmosphere. As can be seen there are certain wavelengths where transmission is very poor. In these regions Water Vapour and CO 2 in the atmosphere absorb the infrared energy. The actual amount of absorption is dependent on path length and meteorological conditions. It is important that thermomers do not operate at wavelengths where there is an absorption band. Thermometers are usually designed to operate in what is known as Infrared Windows, where the transmission is very high. Such regions are 1µm, 1.6µm, 3.9µm, 8-14µm. It is common for thermometers to have a filter in front of the detector to ensure the spectral response is matched to an Infrared Window.



Transmission of infrared through the atmosphere

Semi-transparent Targets

In applications where it is necessary to measure the temperature of a semi-transparent target such glass or plastic film, careful consideration of the materials, transmission, absorption, and reflection should be made.
The infrared energy received by the thermometer from a heated target is the sum of three quantities:

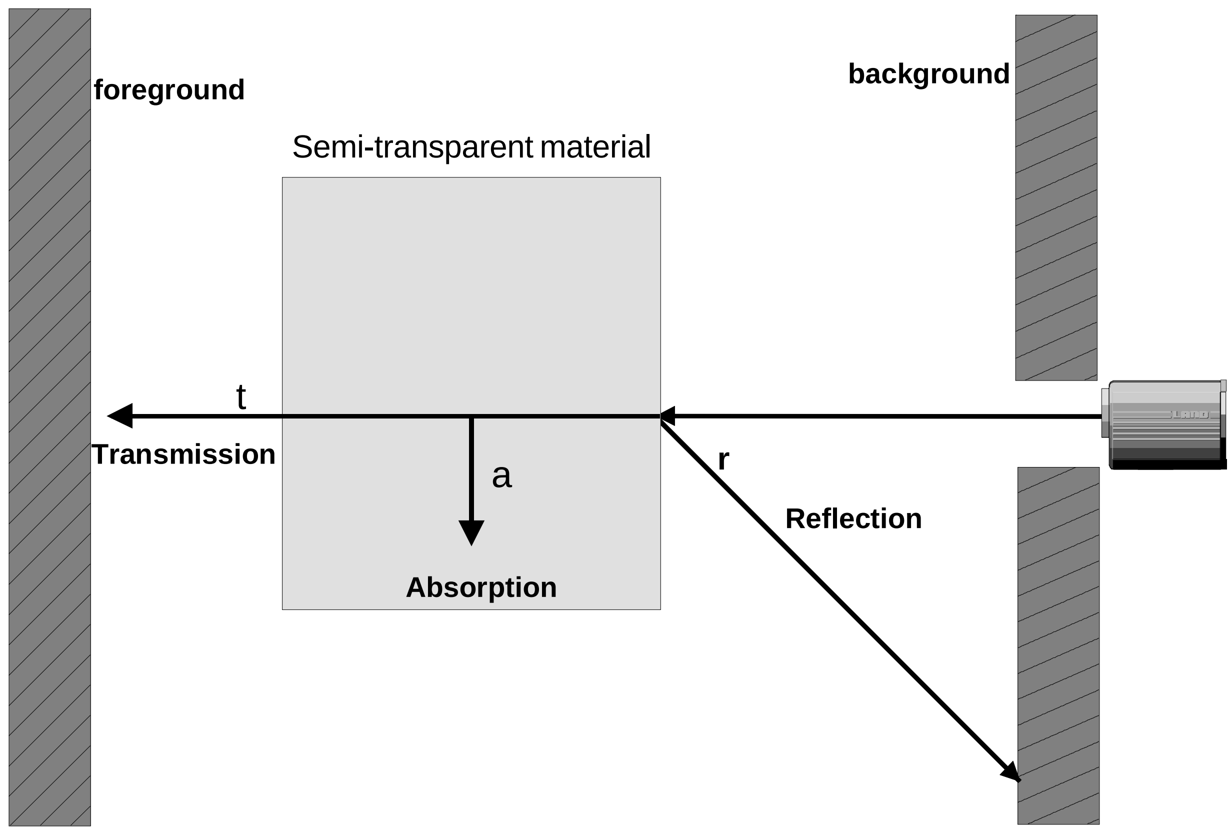
1) The emitted radiation due to the temperature of the target.
2) The background radiation which is reflected from the target.
3) Radiation transmitted through the target.

If a, r, and t are the objects fractional absorption, reflection and transmission respectively then: $a + r + t = 1.0$

The output signal of the thermometer measuring a semi-transparent target is as follows:

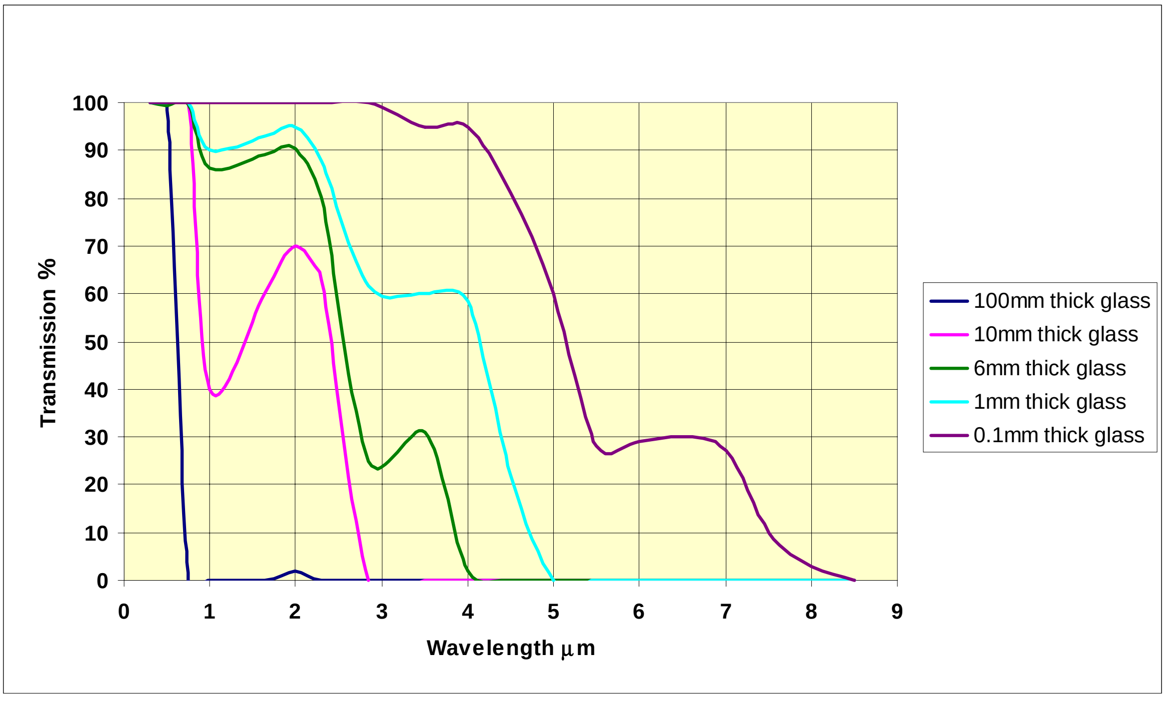
$S = + a.f(T) + r.f(Tb) + t.f(Tf)$
Where:
T = Target temperature, Tb = Background temperature, Tf = Foreground temperature

It is helpful to visualise the measurement situation where it is imagined that the thermometer detector is hot and the resulting emitted radiation tracked to the point where it is absorbed.



Absorption, Reflection and Transmission of semi-transparent materials

As can be seen in the previous diagram there will be a reflection loss at the front surface of the material and a portion of the remaining energy will be absorbed. The energy which is not absorbed or reflected will be transmitted through the material and will end up in the foreground. The absorption and transmission of a semi-transparent material is dependent on material thickness. The transmission of a partially transparent material decreases with increasing thickness. If the reflectivity remains constant the absoption and hence emissivity must increase as the transmission decreases.
The diagram below shows variation of transmission of infrared through glass with thickness and wavelength. As can be seen at a wavelength of 2µm, this particular type of glass will be about 94% transmissive at a thickness of 1mm and about 2% transmissive for a thickness of 100mm.



Transmission of Infrared through glass of various thicknesses

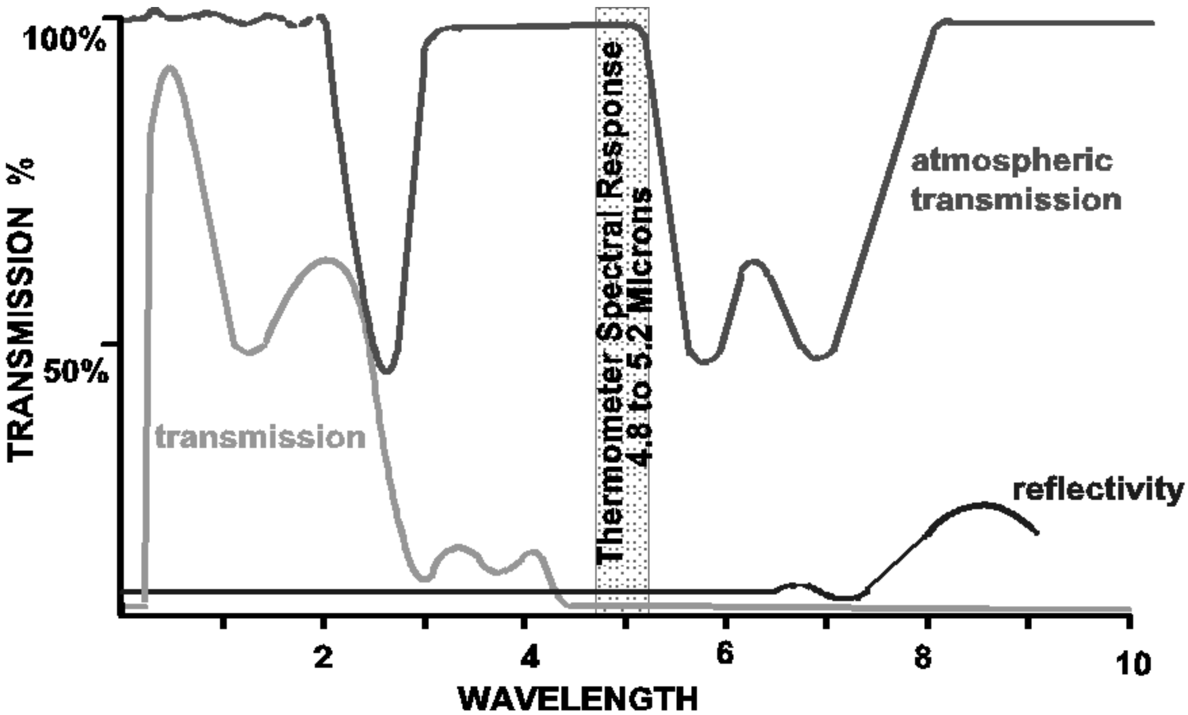
When selecting a suitable thermometer to measure a semitransparent target we must be sure of two things:

1) The target must be measured at a wavelength where the transmission is low to prevent the thermometer from seeing through the target.
2) The target must be of sufficient thickness to ensure that transmission is reduced to a very low value.

Two very commonly measured semitransparent targets are glass and thin film plastics. The measurement of both these materials are now discussed.

Thermometers for the measurement of Glass

Thermometers for the measurement of the surface temperature of a sheet of float glass require careful design.
Short wavelength thermometers tend to see almost completely through the sections of relatively thin glass present in the Float Line tin bath and lehr. This is because minimum absorption occurs in glass at short wavelengths, and this results in very high transmission through the sheet of glass. A short wavelength thermometer could be used however where the glass is quite deep and hence has high absorption, say in the canal section. Maximum absorption occurs at the longer wavelength and hence to measure float glass a longer wavelength thermometer is required. Observation of the graph will show that glass presents a high reflectivity band at wavelengths above 8µm. Use of a typical long wavelength thermometer operating at 8-14µm to measure glass passing through the lehr could result in a large reflected component from the hot surroundings being seen by the thermometer.
The glass thermometer is designed to operate at a wavelength where it is known that the glass is opaque but not largely reflective. A further consideration in the design is to ensure that the thermometer operates in a waveband where the sight path between the thermometer and target is transparent. The spectral regions which contain carbon dioxide and water vapour bands are avoided to ensure the thermometer calibration is not strongly affected by path length and humidity.
The most suitable operating region for the glass thermometer is therefore around 5µm. In this



Selection of a suitable thermometer wavelength to measure glass

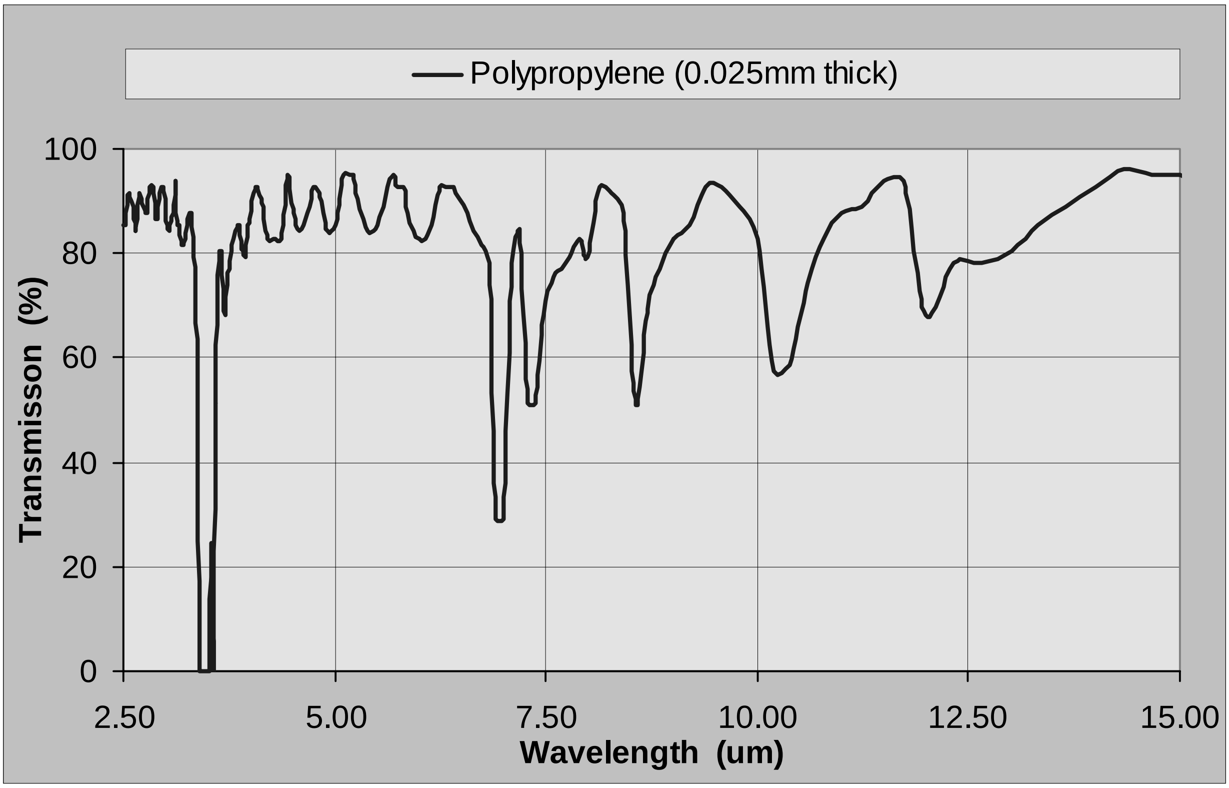
region the glass is opaque, has low reflectivity, and very small sight path absorption.
Thermometers operating at 5µm are used extensively to measure the surface temperature of flat glass on Float Lines throughout the world.

Plastics

Most plastics are processed at relatively low temperatures as they rapidly decompose at temperatures above a few hundred degrees Celsius. Many types of plastic include filler materials to give colour and modify mechanical properties etc. In even moderate thickness these are often opaque over large parts of the infrared spectrum and are therefore easily measured using traditional low temperature wide band thermometers.

Plastic Films:

Thin plastic films have a transmission and hence emissivity which is strongly wavelength dependent.



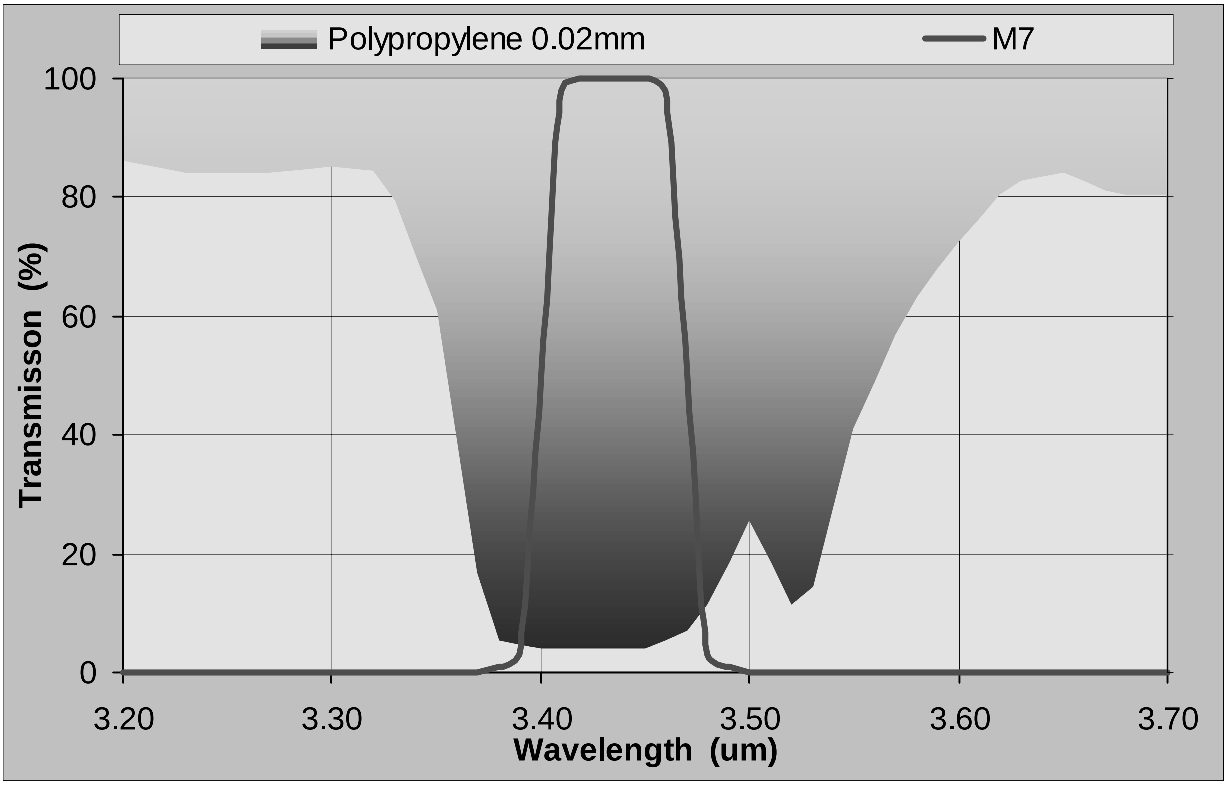
Transmission of Infrared through Polypropylene

The figure above clearly shows how a thin sample of plastic is highly transparent over much of the infrared spectrum. In this case a broad band thermometer will "see" through the sample and will tend to measure whatever is behind it.

The figure also clearly shows a region around 3.4µm where the sample is suddenly quite opaque. In the infrared part of the spectrum this opaque region is associated with particular molecular resonances within the structure of the material.

Many common plastics contain saturated hydrogen to carbon molecular bonds (C-H bond) and it is these bonds which are responsible for the effects seen at wavelengths close to 3.4µm.

Measuerment of temperature of these types of plastic film is often possible if the thermometer is operational at a wavelenth where the plastic film is opaque. Land have developed such a thermometer which is fitted with multi-layer interference filter to precisely locate its sensitivity exactly on the correct wavelength and ensure no sensitivity in the high transmission regions. The graph below shows, in detail, the "3.43µm" opaque region for polypropylene at 0.02mm (20µm) thickness. The thermometer spectral response is perfectly located on the region of highest absorption, and is restricted to only this region, thereby minimising transmission and maximising emissivity.

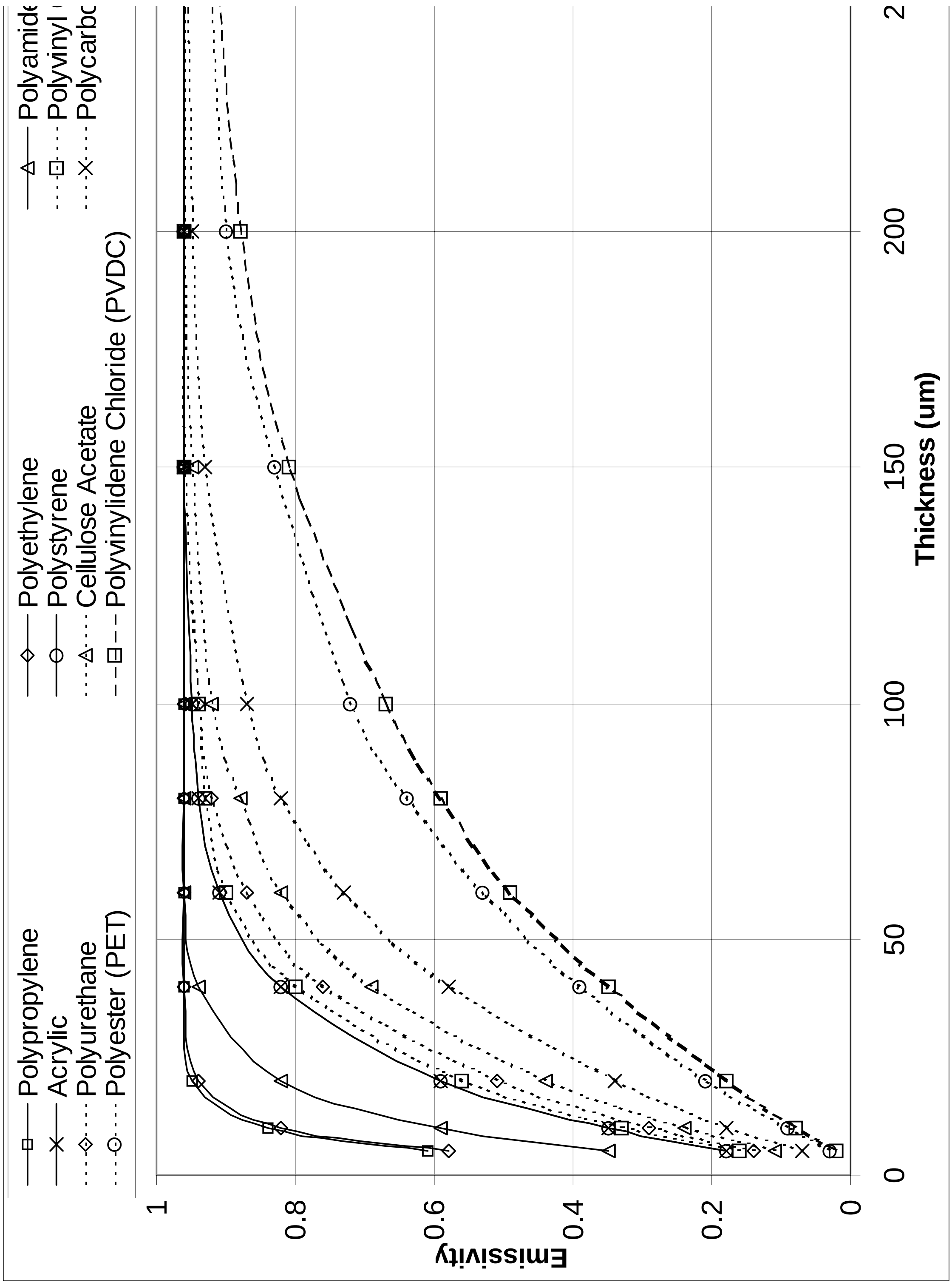


Thermometer spectral response

It should be noted however that plastic materials have many different compositions and not all include the C-H bond. Some plastic films such as polyurethane, acrylic and some fluoro-carbons are not so opaque at 3.43µm and a better result is obtained at 7.9µm (C-O bond). Land have another thermometer operational at 7.9µm and examination of the spectral response of the plastic of interest will show the most suitable thermometer to use.

Emissivity:

The transmission and the reflections from the surface of the target limit the emissivity of any semi-transparent target. For most hydrocarbon plastics the reflection coefficient is 0.04 per surface, and this sets an upper limit of 0.96 for the emissivity even when it is totally opaque. The emissivity value will fall with reducing thickness of the plastic film, leading to an increase in transmission from thebehind the target. It is useful to specify a minimum thickness for a particular plastic material to ensure relaible temperature measurement results.



Emissivity variance with material thickness

It is not recommended that the emissivity setting is used to compensate for inadequate material thickness.
The graph on the previous page shows variance of emissivity with thickness for a variety of plastic film materials at a wavelength of 3.43µm.

Minimum Thickness

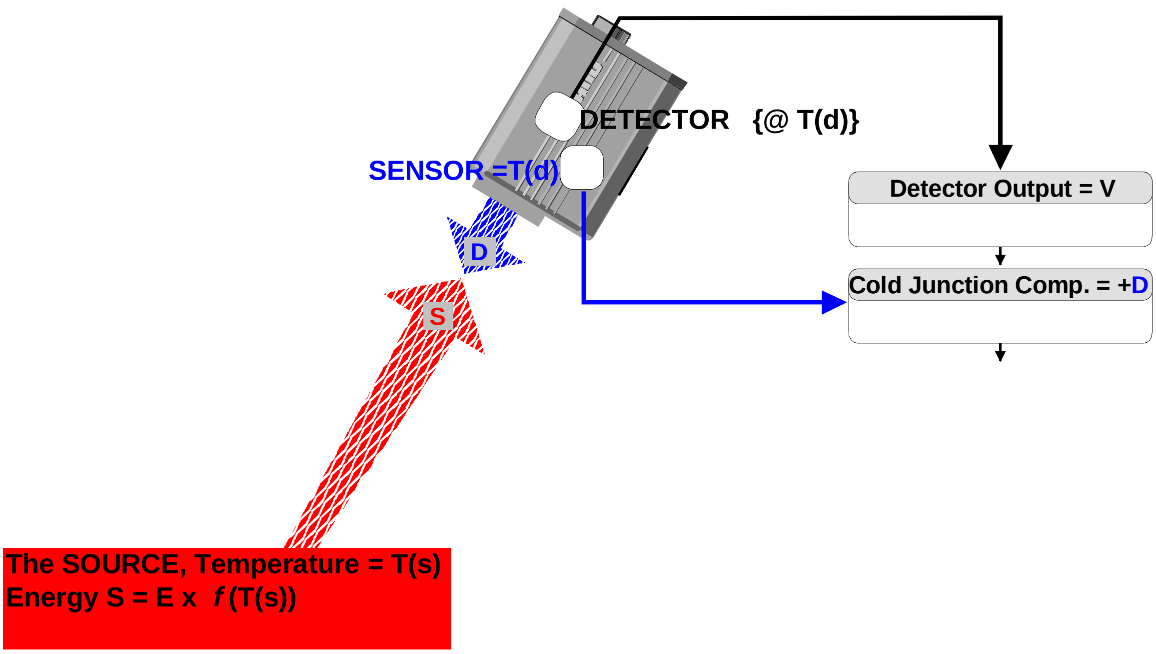
When specifying material minimum thickness, an acceptable transmission value must first be defined.
We have defined the acceptable transmission at a very low value of 2%, resulting in emissivity values of ≥0.94. This definition gives minimum thickness figures which are conservative and which will prove reliable for the vast majority of applications. Minimum thickness to meet this criterion for various plastics is shown in the table below. This Minimum thickness specification should be used with caution as the amount of transmission, which can be tolerated, may vary enormously from one application to the next.

Material	**Min Thickness (for E ≥0.94)**
Polypropylene	20µm
Polyethylene	20µm
Polyamide (Nylon)	40µm
Acrylic	80µm
Polystyrene	80µm
Polyvinyl Chloride (PVC)	100µm
Polyurethane	100µm
Cellulose Acetate	100µm
Polycarbonate	150µm
Polyester (PET)	300µm
Polyvinylidene Chloride (PVDC)	300µm

Minimum thickness of various plastics. Note with 3.43µm Thermometer

Low Temperature Measurement

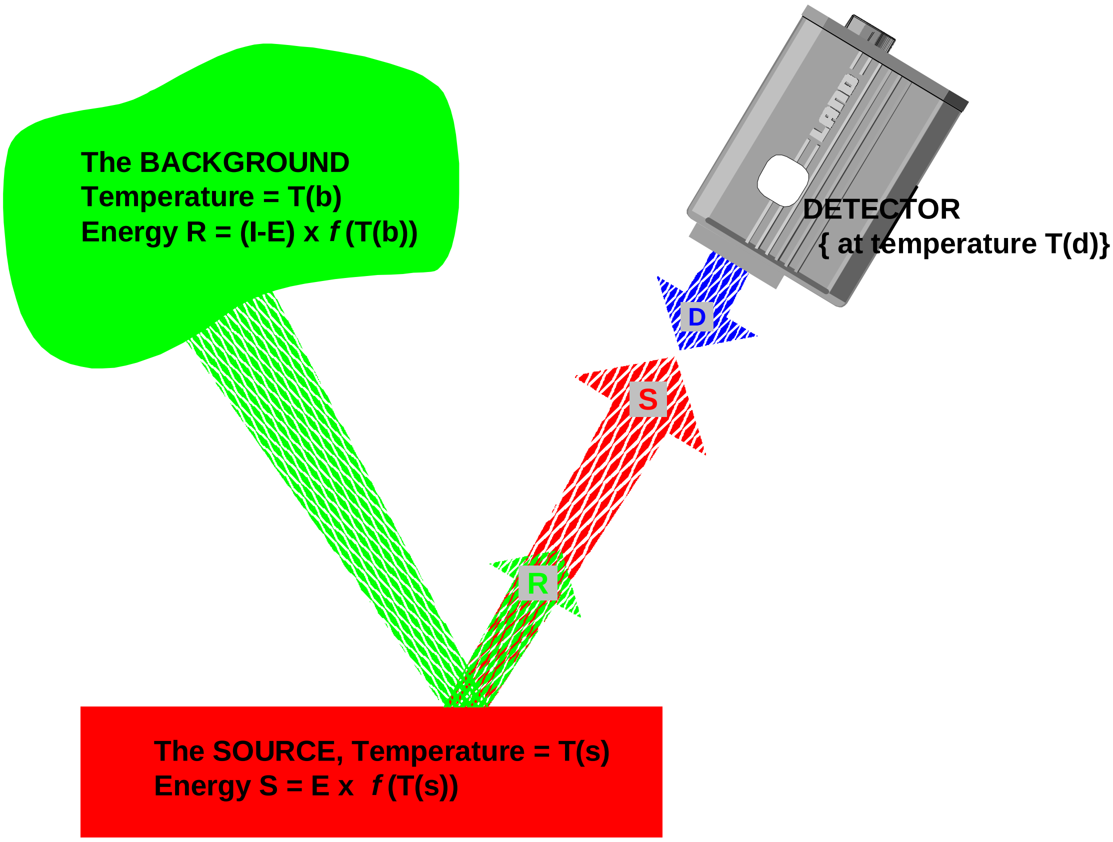
When an infrared thermometer is used to measure a low temperature below say 40°C there are several factors which must be taken into consideration.
Although the target is hot and will radiate infrared towards the thermometer, it should be understood that the because the detector inside the instrument is at ambient temperature it is capable of radiating infrared towards the target. The amounts of energy radiated depend upon the temperature of the target and the detector. The net radiation at the detector is the amount received from the target less the amount emitted by the detector. The situation is analogous to a thermocouple where the output depends upon the difference between the hot and cold junctions. With a thermocouple based measurement system, compensation, called cold junction correction is required to obtain the correct value of temperature. A similar form of compensation is also required in the low temperature infrared thermometer, as the amount of energy radiated by the detector can be comparable with the energy received from the target. The amount of energy radiated by the detector can and does vary with detector temperature which will be influenced by the temperature surrounding the thermometer. To overcome this difficulty the temperature of the detector is measured using a sensor such as a resistance thermometer and the temperature value fed into the radiation thermometers measuring system. This added input makes up for the missing radiation i.e. that emitted by the detector. When measuring higher temperatures for example above 200°C the effect of the energy radiated by the detector is very small and is disregarded.



Net energy received at Thermometer is S - D

Background Reflections:

When the emissivity of the measured target is less than 1.0 some fraction of the total energy reaching the thermometer will have originated in the background and have been reflected by the target into the thermometer. As can be seen in the diagram there are three components to consider.



Reflections from the background

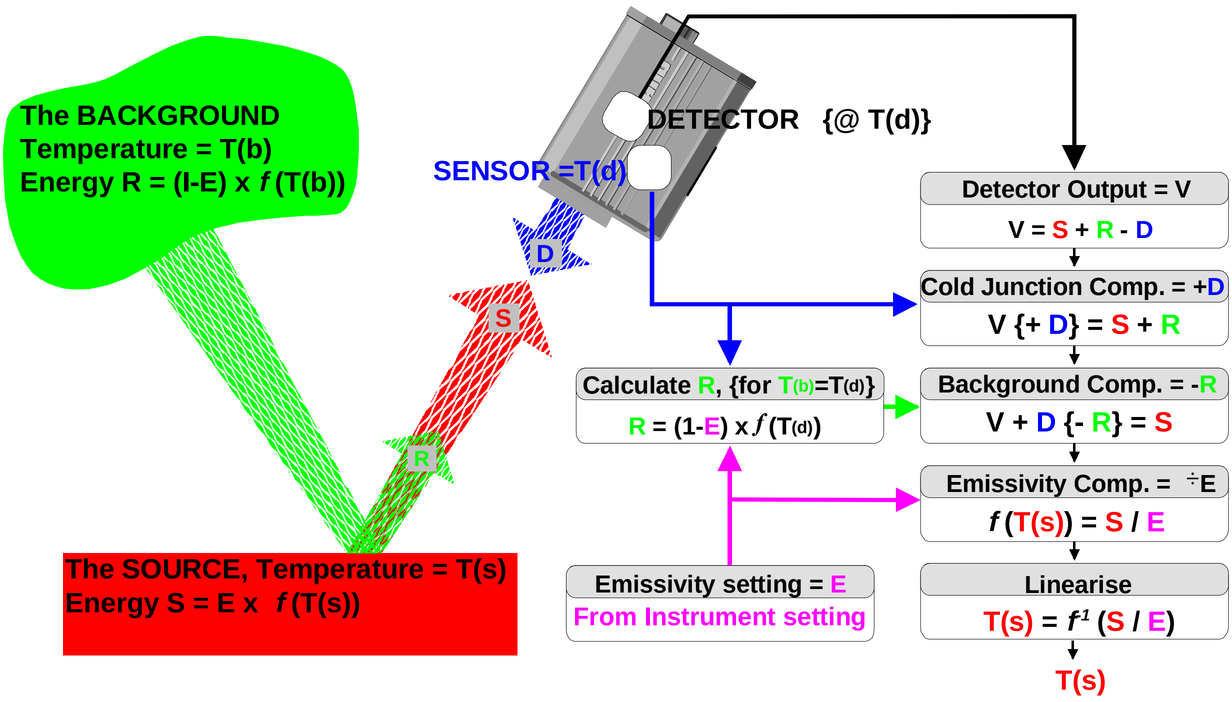
1) The energy radiated out of the thermometer detector D.
   As previously discussed, when the temperature of the detector Td is similar to the target temperature the component D is significant and must be accounted for. A correction for this is made in the thermometer and this is known as 'cold junction correction'.

2) The energy radiated from the target due to target temperature S.

3) Reflected energy from the background R.
   In situations where the background is close or higher than the target temperature the contribution of this component is significant. As the emissivity of the target reduces the reflectivity increases hence increasing the significance of this component.

Signal Processing:

The low temperature thermometer must take into account all the variables as previously discussed.

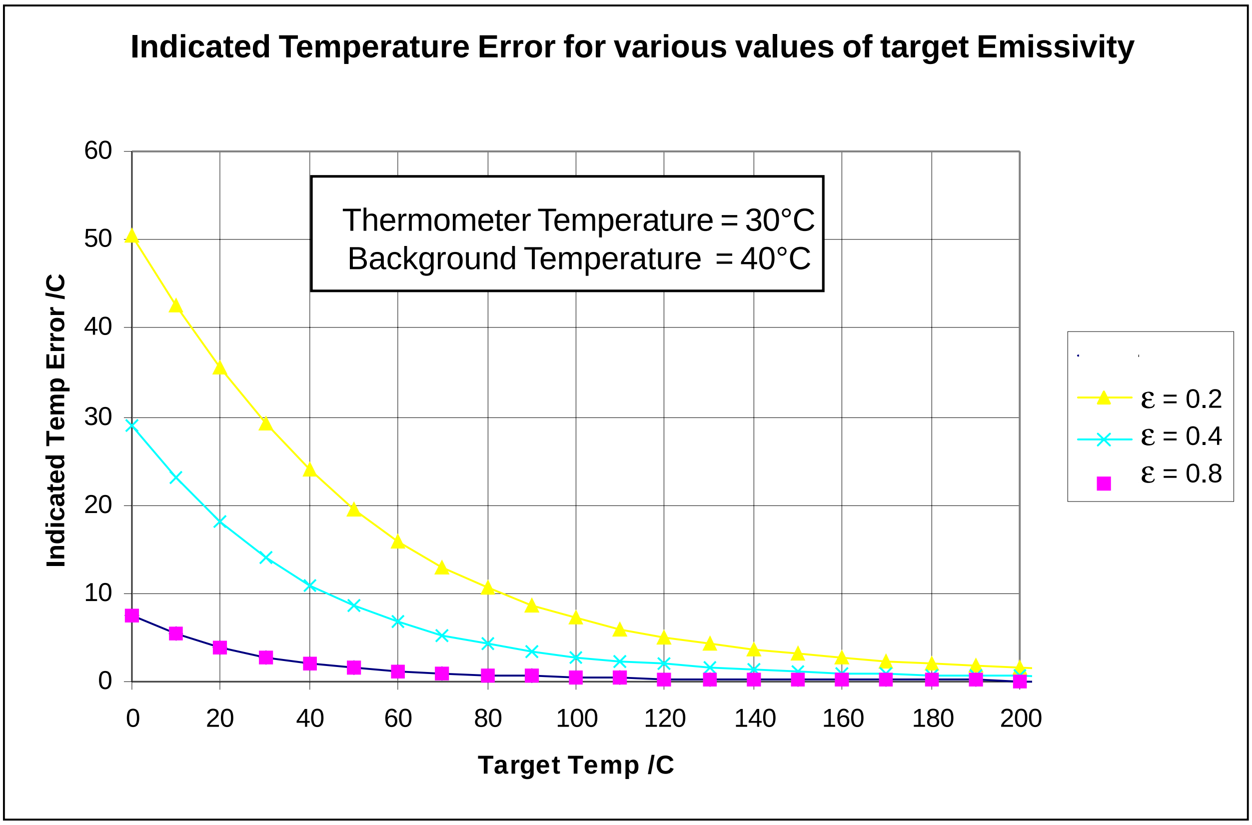


Processing inside the low temperature thermometer

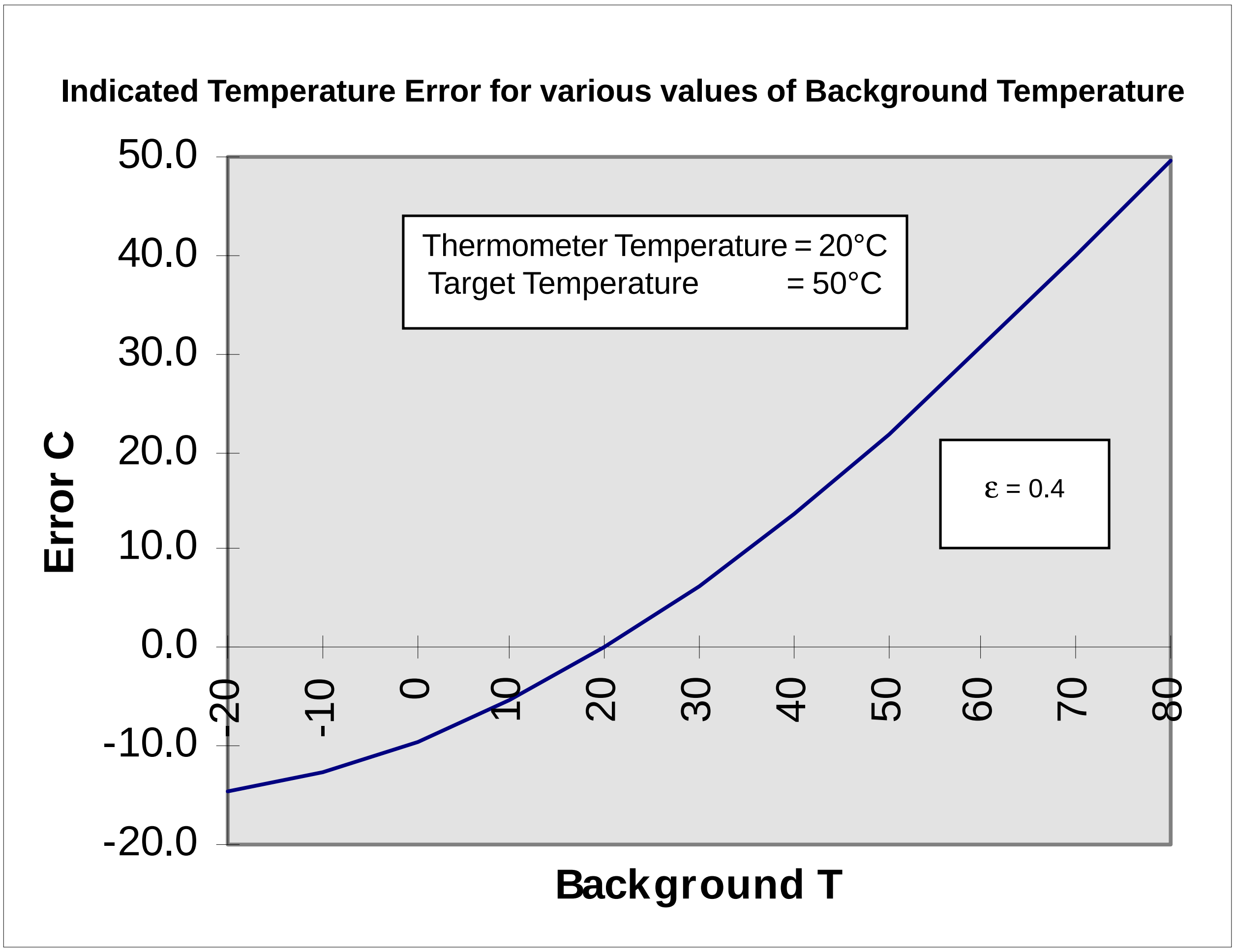
As can be seen in the diagram there are several stages involved in processing the signal.

Step 1: Compensate for the energy radiated from the detector.
This is done by measuring the temperature of the detector and then adding it to the output of the detector.

Step 2: Compensate for background reflections.
The magnitude of the reflected component is dependent upon background temperature and reflectivity of the target surface. The signal processing uses the emissivity setting on the thermometer to obtain a value of reflectivity and multiplies this by an assumed value of background temperature. In this way the value of the reflective component can be obtained and subtracted from the signal after cold junction correction. Commonly it is assumed that the background temperature is the same as the thermometer temperature. This assumption can be somewhat dubious and measurement errors can arise when there are differences in temperature between the thermometer and the background. These errors get worse with low emissivity targets. Graphs on the next page show how significant these errors can be.



As can be seen above there will be errors when assumed background temperature (30°C) does not equal actual background temperature. As the target gets more reflective the error becomes worse.



As can be seen in graph on the previous page there will be errors when assumed background temperature (20°C) does not equal actual background temperature. The error becomes worse as the background temperature increases. It is interesting to note that when the background temperature actually does equal the assumed value of backround temperature the compensation for the reflective component (R) works very well with very little error.
Some thermometers are equiped with an internal adjustment to allow the assumed background temperature to be trimmed to match the actual background temperature.

Step3: The final step is to compensate for emissivity and linearise the signal.

Types of Radiation Thermometers

The most commonly used thermometers tend to fall into one of three possible classes.

1. Broad Waveband

Often referred to as general purpose low temperature thermometers which have a spectral response of 8 to 14µm and will be used on temperature ranges typically of 0 to 250C.

2. Selected Waveband

Usually application specific thermometers which have been designed to overcome special application problems.

Examples of these are 4.8 to 5.2µm thermometer for glass surface measurement and 7.9 µm thermometer for thin film plastic measurement.

3. Short Wavelength

These are usually thermometers which operate below 2.5 µm. A typical example of this is a lµm thermometer which is used at high temperatures such as 600 to 1300C. These thermometers are good at minimising the effect of variable emissivity and are found throughout the steel and other high temperature industries.

4. Ratio Thermometers

The Ratio Thermometer is a dual wavelength device and is often used where the target does not fill the field of view or where there are obstructions in the sight path. Cement Kiln burning zones and wire rod mills are examples of this.

There are many other Application Dedicated Thermomers which have been built with a specific application in mind.
Selection of the most appropriate thermometer for an application can only be made once the details of that application are known. Information such as how hot, how big and how far the target is etc. will need to be known.

For information on products and applications please contact Land Infrared.