Introduction

This document is intended to provide additional information and support to the Foundation Level Infrared Training Course, held at the Land Training School.

It does, however, contain more than sufficient detail to act as a stand-alone introduction to infrared temperature measurement, giving a solid basis in the principles employed in the technique.

This course has been designed to enable the student to obtain a fundamental understanding of how infrared thermometers make temperature measurement. The course uses plain language to explain the principles of non-contact temperature measurement and is particularly suitable to newcomers to the field of temperature measurement by infrared.

We hope you find the course interesting, informative and enjoyable.
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Why Measure Temperature?

For most - in fact all - manufacturing processes temperature is an extremely important variable to measure, monitor and control. Monitoring temperature ensures that the manufacturing process is operating under optimum conditions, which in turn gives improved product quality, increased productivity and reduced downtime.

Along with the quality and productivity benefits brought by temperature measurement, the data may be used to devise preventative maintenance schedules.

A wide variety of sensors are available for temperature measurement. These can be broadly split into two areas; contact measurement, such as thermocouples; and non-contact measurement, such as infrared devices.

CONTACT MEASUREMENT

Thermocouples

The sensor consists of a pair of junctions of two dissimilar metals. When one junction is held at a constant reference temperature (such as 0°C) and the other is placed in thermal equilibrium with, that is in contact with and therefore the same temperature as the object to be measured, a temperature gradient will exist between the two junctions. This temperature gradient will generate a small voltage (potential difference) which is proportional to the temperature difference, hence the temperature of the object can be inferred.
Resistive Temperature Devices

Resistance Temperature Devices, such as a thermistor, are sensors used to measure temperature by correlating the electrical resistance of the device element with temperature. Most elements consist of a length of fine coiled wire wrapped around a ceramic or glass core. Commonly, the element is made from a pure material (usually platinum) whose resistance at various temperatures has been documented.

The wire will have a predictable change in resistance as the temperature changes; it is this predictable change that is used to determine temperature.

NON-CONTACT MEASUREMENT

Infrared

This type of instrument measures the heat - infrared energy - radiated from an object by focusing this energy through an optical system onto a detector. The signal from the detector is then related to a temperature by a series of signal processing functions.

All objects emit infrared energy, the hotter the object the more active its molecules are, hence the more infrared energy it emits.

It is this type of device we shall cover throughout this document, concentrating on the theory and physics behind the measurement, the construction of the thermometer and special considerations for their application.

The Infrared Thermometer clearly offers a distinct advantage over contact measurement due to its ability to determine accurately the target object’s temperature without any physical contact.

Many industrial applications benefit from this technology due to their non-contact nature. Infrared thermometers give the ability to monitor temperature in situations where the object is inaccessible or moving, where the object may be contaminated or damaged by a contact sensor,
where contact is not possible due to extremely high temperatures, or where the object is electrically active.

Since infrared thermometers can determine the temperature of a target object without physical contact, the measurement system does not contaminate, damage, or interfere with the process being monitored and has many advantages over contact measurement devices. An Infrared Thermometer can be mounted remotely from the hot target, enabling it to operate for long periods with minimal maintenance.

Another significant advantage is the very fast response time provided by infrared thermometers, typically a temperature measurement can be made within a few thousandths of a second.

Land Instruments’ Infrared Thermometers are typically used in metal production, glass manufacture and mineral processing, however many more applications exist.
Introduction to Infrared Theory

BACK TO BASICS...

In this section we will discuss the basics of temperature and make some definitions that will provide a good foundation for the terms and principles used later in this document. Consider this as a “gentle” introduction before we start!

Atoms and Matter

Although it may not seem like it, we all have had direct experience of atoms and the forces that hold them together (and apart). Press your finger against a desk or other solid object - the force you feel pushing back is the same force which bonds the constituent parts of the object together and repulses your finger tip, preventing it from passing through the object. Both these forces exist at the atomic level and are responsible for the way different materials interact with each other.

All materials are made from fundamentally the same “stuff” - we can take a material, any at all, and look at the chemical compounds which make up that substance. Chemical compounds in turn, are made from molecules - the smallest constituent piece that behaves, chemically, like the whole substance. The molecules in turn, are made from elements - these are basic materials which cannot broken down into any simpler substance. And here’s the final part: elements are made up of atoms. While its something of an over-simplification, it’s enough to say that different arrangements of atoms produce different elements. More specifically, each atom is made up of a different number of electrons, protons and
neutrons - the exact number of each gives us the different elements and are responsible for determining the chemical, electric and magnetic properties of each.

So how does this all relate to temperature? The atoms possess a certain amount of internal energy and in general terms, the more energy they have, the hotter the object. The atoms in a solid will vibrate around their fixed positions: at low temperatures this vibrational motion is small, but at higher temperatures the atoms will vibrate more energetically. We can also relate the three states of matter (solid, liquid and gas) to temperature and therefore internal energy.

**States of Matter**

Again, in our daily life we will have experienced the three classic states of matter: Solid, Liquid and Gas.

**Solids:** The particles (atoms or molecules) of a solid are packed closely together. The forces between the particles are strong enough so that they cannot move freely, and can only vibrate. As a result, a solid has a stable, definite shape, with a definite volume. Solids can only change their shape by force, as when broken or cut.

**Liquids:** The volume of a liquid is definite if the temperature and pressure are constant. When a solid is heated above its melting point, it becomes a liquid. Inter-molecular forces are still important, but the molecules have enough energy to move relative to each other and the structure is mobile. This means that the shape of a liquid is not definite but is determined by its container. The volume is usually greater than that of the corresponding solid, with the exception of water, which occupies 9% more volume when frozen. The highest temperature at which a given liquid can exist is its critical temperature.

**Gases:** In a gas, the molecules have more energy still, so that the effect of the inter-molecular forces is small, and the molecules are far apart from each other (on an atomic scale) and can move around quickly. A gas has no definite shape or volume, but occupies the entire container in which it is confined. A liquid may be converted to a gas by heating at constant pressure to the boiling point, or else by reducing the pressure at constant
temperature. At temperatures below its critical temperature, a gas is also called a vapour, and can be liquefied by compression alone without cooling.

**Bonding in Solids**

As stated previously, all matter consists of a distribution of atoms and molecules. The atoms in a solid are bound together by electromagnetic forces and held in specific positions. When two atoms are separated by a large distance, the dominant force between them is attractive. If the atoms are brought close together, the force pushes them apart (due to electromagnetic repulsion between the negatively charged electrons with the atom, think of putting two identical poles of a magnet together) and so a minimum distance between the atoms is maintained.

**Thermal Energy**

This electromagnetic bonding force holds all the atoms of a solid in their specific positions, each atom exerting a force on all its neighbours in an atomic balancing act. There is however, a continual motion of the atoms due to thermal agitation: the atoms vibrate around the centre of their fixed positions. The greater the level of vibration, the greater the temperature of the solid.

**Heat**

Contrary to popular use of the term, heat doesn’t refer to the temperature of an object, only the transfer of thermal energy due to a temperature difference. Within an object, thermal energy can be transported as heat by atomic collisions, from an area of high temperature to an area of low temperature. An object contains or stores thermal energy, not heat. Once the energy is transferred, it can no longer be called heat and must be referred to again as thermal energy.
Definitions: the difference between heat, temperature and internal energy

Temperature is a measure of the average kinetic energy of the atoms which make up a substance, while Internal Energy is the total energy of all the atoms in the object. Heat is the transfer of this energy from one object to another due to a temperature difference.

So, what exactly is temperature?

We all have an intuitive notion of what temperature is - the physical property of a system that we perceive as being hot or cold.

On the molecular level, temperature is defined as the average energy of microscopic motions of particles which make up a substance. For a solid, these microscopic motions are principally the vibrations of the substance’s constituent atoms about their sites within the solid. As heat energy is supplied to an object, the average energy of these motions increases, causing a rise in the temperature of the substance.

Temperature Measurement and Scales

Clearly, if we wish to measure the temperature of an object, we need to have some fixed reference points by which to do so. However, before we look at temperature scales, we must first define something known as the Zeroth Law of Thermodynamics, a particularly odd title for historic reasons - the First, Second and Third laws had already been defined when the fundamental importance of the “Zeroth” law was realised. Essentially, it states that if two separate bodies are at thermal equilibrium with a third body (ie at the same temperature with no heat transfer between them), then they must also be in thermal equilibrium with each other. Take a moment to read that again. The implication of this law is the fundamental principle by which thermometers operate. If one of these three bodies is an instrument calibrated to measure temperature, then the fixed temperature point in one body, as measured by our thermometer, must also represent the same fixed temperature point in the separate body at thermal equilibrium.
We must therefore choose some sensible fixed points by which to define a
temperature scale. In 1724, Daniel Gabriel Fahrenheit did this by setting
the zero point to the coldest temperature he could produce, a mixture of
water, ice and salt. He placed a mid-point at the freezing point of water,
and the upper point at normal body temperature for which he choose a
value of 96. Later work on the scale lead to a slight revision which gives
180° between the freezing point and boiling point of water, 32°F and
212°F respectively, setting body temperature at 98.6°F.

Anders Celsius, in 1742, took a slightly difference approach: using the
freezing and boiling point of water as reference temperatures, he then
divided the scale into 100 degrees, or centigrades. This gave 0°C as the
freezing point and 100°C as the boiling point of water.

Now let us return to the idea of temperature of an object being related
to the vibrations of its constituent atoms. It follows that if the vibrations
become more energetic as temperature increases, then they must become
less energetic as the temperature decreases - to the point at which they
completely stop. The process of cooling an object involves removing
energy from the system - when no more energy can be removed from
a substance, the system is said to be at absolute zero. This is the point
on the Absolute Temperature Scale, proposed by Lord Kelvin, William
Thompson, in 1848, where all kinetic motion of the particles comprising
the matter ceases and they are at complete rest. By definition, absolute
zero is a temperature of zero Kelvin, which turns out to be –273.15°C or
–459.67°F.

The Absolute Temperature scale, measured in Kelvins, uses the same
degree increment as the Celsius scale; an increase in temperature of
1°C equals an increase in temperature of 1K (note the lack of a degree
symbol). Essentially, the whole scale is “shifted” by -273.15°. Conversion
to Fahrenheit from Celsius is a little more complicated and requires the
use of a conversion factor: [°F] = [°C] × 9/5 + 32.
Modes of heat transfer

There are three ways, or modes, in which thermal energy can be transferred between bodies: conduction, convection and radiation. In order to make infrared temperature measurements we are concerned with radiated energy only.

*Conduction:* This is the only mode of heat transfer in solids. It occurs as the result of molecular collisions in liquids and atomic vibrations in solids. Each collision passes on energy, resulting in the flow of thermal energy from hot to cold areas. It should be noted that conduction can only occur between objects which are in direct contact.

*Convection:* This mode of heat transfer takes place in a moving medium and is normally associated with heat transfer between a solid and a moving fluid, such as air. We can consider two types of convection: *Forced* and *Free*. In forced convection, an external driving force, such as a pump, moves the fluid. Free convection occurs when temperature
differences produce a density gradient within the fluid and the warmer fluid rises as a result of buoyancy.

**Radiation:** This occurs in a very different manner from the other two modes of heat transfer. The energy transfer takes place in the form of electromagnetic emission and absorption (the same mechanism responsible for visible light, radio waves and even x-rays), it therefore occurs at the speed of light and can travel through a vacuum.

Electromagnetic radiation is a wave which has both electric and magnetic components. The frequency of the oscillation determines how the wave interacts with matter. At certain wavelengths we see visible light, the actual wavelength determining the colour we see. At long wavelengths we can use the energy to transmit signals over great distance; radio waves. At short wavelengths we can use the electromagnetic waves to inspect the inner workings of our bodies; x-rays.

Electromagnetic radiation in the region which transmits thermal energy is known as infrared and for the purpose of temperature measurement occurs with wavelengths between 0.0005mm and 0.0015mm. In order to simplify things a little, we can use a unit of measurement known as the “micron” with the symbol “µm”. One micron, 1µm, is one millionth of a metre. Therefore, the infrared region we are interested in occurs at 0.5µm to 15µm.

**Thermal Radiation**

Again, the concept of thermal radiation is quite intuitive: what we feel as heat from an object, without touching it, is thermal radiation. Any object whose temperature is above absolute zero, will possess thermal energy, related only to its temperature, and will radiate a portion of this as infrared energy. In general, the higher the temperature, the more energy this object will emit. An object may also become heated by absorbing infrared waves - in fact, the human body is capable of emitting and absorbing infrared energy. This is the reason why we feel warm in bright sunlight. The infrared emissions from the sun reach us after travelling through space and the Earth’s atmosphere at the speed of light.
If an object is hotter than its surroundings, it will emit more radiation than it absorbs, and will tend to cool down, conversely, if the object is cooler than its surroundings, it will absorb more radiation than it emits, and will tend to warm up. Usually, the object will (eventually) come to thermal equilibrium with its surroundings; at this point the rate of absorption and radiation of infrared energy will be equal.

Thermal radiation is electromagnetic radiation emitted from the surface of an object which is due to the object’s temperature. Thermal radiation is generated when energy from the movement of charged particles within the object’s atoms is converted to electromagnetic radiation.

**ELECTROMAGNETIC RADIATION**

Electromagnetic radiation (EM) is a self-propagating wave (in a vacuum or in matter) with electric and magnetic components. These components oscillate at right angles to each other and to the direction of propagation, and are in phase (Figure 1).

Electromagnetic radiation is classified into types according to the frequency (wavelength) of the wave: these types include, in order of increasing frequency, radio waves, microwaves, terahertz radiation, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.

![Figure 1: Electromagnetic Radiation](image)

The wavelength of an electromagnetic wave in a vacuum is related to frequency by:
\[ f = \frac{c}{\lambda} \]

- \( f \) = frequency, Hz
- \( c \) = speed of light, ms\(^{-1}\)
- \( \lambda \) = wavelength, m

A radiation thermometer determines the temperature of an object by measuring the electromagnetic energy it emits. All objects are capable of radiating electromagnetic energy which will propagate through space at the speed of light.

**THE ELECTROMAGNETIC SPECTRUM**

The electromagnetic spectrum contains many different forms of electromagnetic emissions, including infrared, visible light, X-rays, radio waves, and several others (Figure 2). The only difference between these emissions is their wavelength (related to frequency, as above).

Radiation thermometers are designed to respond to wavelengths within the infrared portion of the spectrum. In practice, temperature measurement is made using thermometers which are operational over many different ranges of wavelength, which generally reside between 0.5 to 15µm.

![Figure 2: Electromagnetic Spectrum](image)

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 us the ability to observe the temperature of a metal being heated.
This is seen in the form of a change in colour (wavelength) of the metal from dull red through to bright white.

Most infrared emissions are outside the range of the human eye and therefore cannot be observed. They can, however, still be focused by an optical system on to a detector inside an infrared thermometer in a similar way to visible light in a photographic camera.

**MORE ON THERMAL RADIATION...**

The spectrum of thermal radiation from a hot body is continuous: for any given temperature, the object will emit electromagnetic radiation in a continuous range of wavelengths.

It is also important to note that thermal radiation depends not only on temperature, but the composition and surface condition of the object. Different materials will emit radiation at different rates - an unoxidised stainless steel alloy (with say a composition of 8% Ni & 18% Cr) at a temperature of 2000K (1727°C) will emit infrared energy at a rate of 32 W cm$^{-2}$, while polished aluminium plate at the same temperature will emit just 5 W cm$^{-2}$. In both cases, the rate can be somewhat increased by roughening of the surface.

Now let us consider the emissions from an ideal object, a blackbody (more on this later!). The spectrum of wavelengths emitted is a probability distribution depending only on an object’s temperature. For a blackbody object, the intensity vs. wavelength is given by the Planck Radiation Law.

Thermal radiation, even at a single temperature, will occur over a wide range of wavelengths. How much at each wavelength, is given by Planck’s law of radiation:

\[ J_{\nu}, \partial \lambda = \frac{C_1}{\lambda^5 e^{C_2/\lambda T} - 1} \]

- $J_{\nu}, \partial \lambda =$ Blackbody radiation emitted at temperature $T$, °K
- $\lambda =$ Wavelength, m
- $C_1 =$ Planck’s First Constant, $3.74 \times 10^{-16}$ Wm$^2$
- $C_2 =$ Planck’s Second Constant, $1.4388 \times 10^{-2}$ m K
The wavelength of the peak energy radiated will decrease as the temperature increases. For example, a red hot object radiates most energy in the long wavelengths of the visible band (short wavelength infrared, ~0.6µm), which is why it appears red. If it heats up further, the peak wavelength shifts to the middle of the visible band, and the spread of frequencies makes the object appear white. We then say the object is white hot.

We now need to look at two further equations: Wien’s Displacement Law and the Stefan-Boltzman Law.

Wien’s Displacement Law gives the wavelength of the peak energy of the radiation distribution, while the Stefan-Boltzman Law gives the total energy emitted at all wavelengths by the blackbody (the area under the Planck Curve). It can be seen from Wien’s Law that peak energy shifts to the shorter wavelengths as temperature increases. From the Stefan-Boltzman Law, the peak energy level increases with the forth power of the temperature.

Studying both these equations explains why the peak shifts to shorter wavelengths as temperate increases, and why peak level increases as the temperature increases.

Figure 3 shows the distribution of energy across the infrared portion of the electromagnetic spectrum for an object at varying temperature.
Figure 4 shows the relative amounts of energy emitted by an object when heated to different temperatures across the infrared spectrum. Again, this shows the characteristic of peak energy emitted at increasingly short wavelength for increasing temperature.
ABSORPTION, TRANSMISSION AND REFLECTION

When the infrared energy 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 components must always add up to the initial value of radiation which left the source.

As shown on Figure 5, we can say that if $a$, $r$, and $t$ are the body’s fractional values absorption, reflection and transmission, then:

$$a + r + t = 1$$

It then follows that if a large fraction of the radiant energy is transmitted through the object, the material can be regarded as transparent.

In contrast, if the reflectivity $r$ is very high, the object is considered to be mirror-like. Other material types which have poor transmission and poor reflection characteristics generally absorb much of the radiant energy incident on their surface. The absorption of any material generally increases as the surface roughens - for an opaque material, as the surface
is roughened the reflectivity decreases, causing a proportional rise in absorptivity.

**BLACKBODY RADIATION**

Kirchoff’s Law of thermal equilibrium states that: *At thermal equilibrium the energy radiated by an object must be equal to the energy absorbed by that object.*

If we consider an object $S$ in a vacuum chamber whose walls are maintained at a uniform temperature $T$, then at thermal equilibrium, the object must reach the same temperature as the chamber walls.

It then follows from Kirchoff’s Law, that radiation from the walls incident on and absorbed by the object must equal the radiation emitted by the object. For objects whose absorption ability is less efficient, then their emission ability will be correspondingly lower.

In this instance, we can express Kirchoff’s Law as:

$$a = \varepsilon$$
where $\varepsilon$ is a number between 0 and 1, expressing the emissive characteristic of a surface - a property known as emissivity (more on this in the next section - keep reading!).

This leads onto a very important concept - that of the perfect absorber/perfect emitter - the “blackbody” object. The blackbody is an ideal surface having the following properties:

- A blackbody absorbs all incident radiation, regardless of wavelength and direction;
- For a given temperature and wavelength, no surface can emit more thermal radiation than a blackbody;
- The radiation emitted by a blackbody is independent of direction.

In a blackbody object, the total radiant power and its spectral distribution depend only upon temperature. For this reason, artificial blackbodies are used for calibration of infrared thermometers.

A quick summary:

“An object which is totally non-reflective and completely opaque will absorb all the radiated energy received incident on its surface. This type of body is a perfect absorber and will therefore be a perfect emitter of infrared radiation; referred to as a blackbody object.”

It is worth noting that a blackbody object is a purely theoretical device: in practice, we find that the surfaces of materials are not perfect absorbers and tend to both emit and reflect infrared energy.

A non-blackbody object would absorb less energy than a blackbody object under the same conditions. Hence, it would radiate less infrared energy, even though it was at the same temperature.

The understanding of a surface’s ability to radiate infrared energy is very important to achieve accurate measurements with infrared thermometry.
Emissivity

The emissivity of a material, usually denoted as $\varepsilon$, is the ratio of the energy radiated by the material to the energy radiated by a black body at the same temperature. It is a measure of a material’s ability to absorb and radiate energy. A true black body would have an $\varepsilon = 1$ while any real object would have $\varepsilon < 1$. Emissivity is a numerical value and does not have units.

Figure 6 shows why objects are not perfect emitters of infrared energy. The atoms of an object will have both vibrational and translational motion. This motion causes collisions between the object’s atoms – occasionally, a collision will increase an atom’s energy and an electron will be “pushed-up” into a higher energy level. When the electron drops back down, it emits electromagnetic energy (or more strictly, a photon). When this
electromagnetic energy reaches the boundary of the object (ie the surface), a portion will be reflected back inside, and a portion will be radiated out. This internally reflected energy will never leave by radiative means.

The ability of a material to radiate infrared energy depends upon several factors: the type of material, the surface condition, the wavelength and the temperature all have an effect on the object’s emissivity to varying degrees. The value of emissivity for an object is an expression of its ability to radiate infrared energy.

**Emissivity and Reflectivity**

To make a more concise statement, blackbody radiation, at a level defined by the Planck Formula, exists within a solid body, which we know is largely empty space - the “gaps” between the atoms. When this radiation reaches the boundary of the body a fraction \( R \) is reflected and the remaining fraction \((1-R)\) is emitted.

\[
(1-R).B = \varepsilon.B
\]

\( R \) is the reflectivity of the surface 
\((1-R)\) is the emissivity of the surface = \( \varepsilon \)

Thus emissivity is:

\[
\varepsilon = \frac{\text{Radiation emitted by target at temperature } T}{\text{Radiation Emitted by a Blackbody at Temperature } T}
\]
The table below shows some typical, real-world values for emissivity for various materials.

Observation of the 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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity at 1µm</th>
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<tr>
<td>Unoxidised Steel</td>
<td>0.35</td>
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<tr>
<td>Oxidised Steel</td>
<td>0.85</td>
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<tr>
<td>Unoxidised Aluminium</td>
<td>0.13</td>
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<td>Oxidised Aluminium</td>
<td>0.40</td>
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<td>Unoxidised Copper</td>
<td>0.06</td>
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<tr>
<td>Oxidised Copper</td>
<td>0.80</td>
</tr>
<tr>
<td>Brick</td>
<td>0.80</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0.85</td>
</tr>
<tr>
<td>Asbestos</td>
<td>0.90</td>
</tr>
</tbody>
</table>

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 their effect on emissivity values:

**Effect of Wavelength**

It should be noted that in the table above the emissivity values are specified for a given wavelength. Emissivity will normally vary with wavelength - for example, the emissivity of polished metals tends to decrease as wavelength becomes longer. Non-metallic materials tend to behave differently to metals often showing large variations of emissivity with wavelength. Semi-transparent materials such as plastic film also show strong variations with wavelength and require special consideration.
Figure 7 shows the typical emissivity curve for iron, along with a “greybody” object which has a constant emissivity across the whole of the infrared spectrum.

\[ \text{Figure 7: Emissivity vs. Wavelength} \]

**Effect of 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 a high temperature industrial process 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.

**Effect of Viewing Angle**

The emissivity of most materials is not strongly dependent on viewing angle provided measurement is made within about 45° of normal (Figure 8). The maximum recommended angle for mounting an infrared thermometer is 45°.
Effect of Temperature

The emissivity of materials does not tend to vary with temperature when using a thermometer which operates over a narrow waveband. Emissivity will usually only change with temperature if the surface properties of the material change, for example if coatings become tarnished or degraded.

WHICH EMISSIVITY VALUE?

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

- Consult Land’s operating instructions, which list typical emissivities for each model variant of thermometer. Caution should be used when applying emissivity values from other sources to ensure that the wavelength (and temperature) at which these were determined is the same as the operational wavelength of the thermometer in question.

- Determine the emissivity by a laboratory method. Usually performed by making a comparison between measurement of an objects’s temperature by contact and infrared methods.
EFFECT OF EMISSIVITY ON TEMPERATURE MEASUREMENT

As radiation thermometers are calibrated against blackbody 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 provided on the thermometer, which when set to the value of emissivity of the target, will compensate for the non-blackbody nature and enables the correct temperature to be measured.

To make an accurate and reliable temperature measurement, it is necessary to know the emissivity of the target material. This may not pose a problem in industrial applications, which are inherently repetitive, and when the emissivity of the target may be considered a fixed quantity with some uncertainty. In practice, measurement using infrared methods is usually possible. It should be understood however, that in certain applications notably where bright, lightly oxidised metals are involved that measurement solutions may be difficult or not even possible.

![Figure 9: Measurement Errors](image)

Figure 9 shows the expected error in indicated temperature for a short wavelength infrared thermometer, looking at a target of 1000K with variable emissivity. If no emissivity compensation is employed, it can be seen that as the emissivity of the target material decreases, the infrared thermometer will “see” less energy and therefore report a lower temperature than the true value.
WAYS OF CORRECTING FOR EMISSIVITY

If the emissivity of the surface is known, the operator can set this value somewhere in the measuring system. The system uses this value as a compensation factor to eliminate the effect of the non-blackbody nature of the target, by multiplying the detector signal by $1/\varepsilon$.

Emissivity compensation will normally be applied before signal treatment such as linearisation

COPING WITH EMISSIVITY

We can adopt one of several possible approaches which can help minimise emissivity uncertainty. A good first choice is to use the shortest possible wavelength thermometer. Sometimes due to special measurement conditions, this is not enough. In this case, there are some techniques available to “enhance” the emissivity to make an accurate, reliable measurement.

Use the shortest possible wavelength thermometer

The energy emitted by a hot target changes very rapidly at short wavelengths, but more slowly at long wavelengths. As a result thermometers which operate at short wavelength minimise the errors which occur with change in target emissivity.

Figure 10 shows a comparison between the errors expected from a short wavelength thermometer (red trace) and one which operates at long wavelength (blue trace) with changes in target emissivity.

It can be seen that the error from the short wavelength thermometer is about $10^\circ$C for a 10% change in emissivity for a target at $1000^\circ$C. The long wavelength thermometer gives much greater errors with similar changes in target emissivity.
It can be seen that in the event of a 20% reduction in energy from the target (a change in emissivity from 1.0 to 0.8), the reduction in indicated temperature (or error) from the short wavelength thermometer is in the order of 20°C. The response from the long wavelength thermometer shows a reduction in indicated temperature in the order of 80°C for the same change in target energy.

Figure 11 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, possibly due to a change in target emissivity, will result in a fall in indicated temperature of only 1°C. This translates to an error of 0.1% in temperature.
It is often a good solution to fit a thermometer with the shortest possible wavelength. This 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 in applications involving the temperature of semi-transparent 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 ~0.99 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.

**Black Body Cavities**

As already stated, for an opaque object, \( Emissivity + Reflectivity = 1.0 \). When incident radiation reaches an opaque flat object, a portion will be absorbed and a portion will be reflected. The amount of fractional absorption and reflection determine the emissivity of the object. If reflectivity = 0, then the emissivity = 1.0 and the object can be said to be a black body.

Black Body radiation will exist in any enclosure or cavity whose walls are at a uniform temperature. The radiation level is defined by the temperature only (by Planck’s Law): It is independent of the shape and size of the enclosure and wall material.

Figure 12 shows incident radiation entering a cavity. This incident radiation 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 blackbody cavity is fundamental when constructing a reference source for calibrating infrared thermometers.

A quick summary: “A cavity that is at least six times deeper than its width will appear to a radiation thermometer to be (almost) a black body.”

**APPLICATION OF EMISSIVITY ENHANCEMENT BY MULTIPLE REFLECTION**

Natural cavities in products or between process and product can be exploited to solve the problem of low and variable emissivity.

Figure 13 shows an interesting example where a thermometer has been sighted to look into the cavity formed between a process roller and hot steel strip 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.
The thermal image below shows the emissivity enhancement in the “wedge” of a coil of rolled aluminium. The effect can be seen in the image as the brighter yellow section, even though the whole of the aluminium coil is at the same temperature.

**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 was one of Land’s first instruments (developed in the early 1950’s) and had a detector looking into a gold plated hemisphere which was mounted on the end of a telescopic arm. When placed on the surface
of a material, the emissivity inside the hemisphere 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.

A development of this system is the Land Emissivity Enhancer, available in our current range of online thermometers. This device uses a non-spherical (parabolic) reflector and again employs the principle of emissivity enhancement by multiple reflections. The Enhancer is fitted to the protection jacket of a thermometer and has been shown to give effective emissivity values comparable with the Surface Pyrometer but at distances of up to 30mm from the target surface. A schematic of the Land Emissivity Enhancer is shown in Figure 14.
SCALE SHAPE

The scale shape of a radiation thermometer is the relationship between the radiation power detected by the pyrometer and the target temperature. This can be calculated from Planck’s Law once the spectral response of the pyrometer is known. From the scale shape, or by calculation, it is possible to determine the percentage change in output for a 1°C rise in target temperature. This is a very useful value, known as Percent-per-Degree (%/°C), which is enables us to evaluate the amount of measurement error for a given change in target emissivity. As the scale shapes for thermometers are non-linear, the value of %/°C will vary with temperature. The %/°C value will also varies with operational wavelength of the thermometer.

The Percent-per-Degree (%/°C) value is obtained as follows:

\[
\%/°C = 100 \times \frac{C_2}{\lambda T^2}
\]

\[C_2 = \text{Planck's Second Constant, } 1.4388 \times 10^{-2} \text{ m K}\]

\[\lambda = \text{Operational wavelength of thermometer}\]

\[T = \text{Temperature of target object, K}\]

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

\[
\%/°C = 100 \times \frac{14388}{1 \times 1000^2}
\]

\[= 1.44\]

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

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

From the above calculation, a 1µm thermometer has a %/°C value of 1.44 at 1000K. If the emissivity of a target changes by ±5%, the measurement error may be calculated as follows:

\[
\text{measurement error} = \frac{5.0}{1.44}
\]

\[= 3.47°C\]
It should be clear that a high %/°C value reduces the effect of change in target emissivity, improving the accuracy of the measurement. High values of %/°C are obtained at short wavelength, since the energy emitted by a hot target changes rapidly at short wavelength, and values tend to improve as the target temperature reduces.

Figure 15: Error due to Emissivity Variance

Figure 15 shows expected errors in temperature, in °C, in the event of a 1% error (or variance) in emissivity. Note how the shorter wavelength thermometers return smaller errors than the long wavelength thermometers.
Different Measurement Cases

reflectivity

We have seen that when radiation from the interior of a body reaches its internal surface, it is partially reflected. This process will also occur to the same degree to radiation incident on the external surface of the body.

Thus, the radiation leaving the surface is the sum of the emitted and reflected radiation. The former depends on the temperature of the body, the latter on the (average) temperature of the surrounding environment. The thermometer however, 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 then consider three possible measurement cases; a hot target in a cool environment; a hot target in an environment of the same temperature and a hot target in a hotter environment.
A HOT TARGET IN COOL SURROUNDINGS

When the thermometer is presented with a hot target in cool environmental surroundings, the ambient radiation is low, and for short wavelength thermometers, can be ignored. A real-world application of this condition is hot product at the Roughing Stand of a Steel Rolling Mill, where there will be hot steel, at approximately 1000°C, on rollers in normal ambient temperatures.

The output from the thermometer would be:

\[ V = \varepsilon \times B + I \times R \]

- \( B \) = Internal blackbody energy
- \( I \) = Incident Infrared Energy
- \( R \) = Reflectivity \((1 - \varepsilon)\)

As the surroundings are cool in comparison to the target the reflected component \( IR \) can be ignored.

A HOT BODY IN SURROUNDINGS AT THE SAME TEMPERATURE

When the thermometer is presented with a hot target in an environment with the same background temperature, this results in blackbody conditions. This situation is observed when measuring steel in the Soaking Zone of a Steel Rolling Mill Reheat Furnace or on measurement of molten glass inside the Glass Furnace Forehearth. Prior to the steel entering the rolling mill, the steel stock is heated in a reheat furnace. The stock is passed through the furnace using either a walking beam device, which lifts and advances the stock, or a pusher system where the stock
is pushed through the furnace on water cooled skids. The furnace has
normally three controlled temperature zones, which raise the temperature
of the stock as it moves through the furnace. These are known as the
pre-heat zone, heating zone and soaking zone. The soaking zone is used
to ensure that the stock is thermally homogeneous before it is discharged
from the furnace on to the roller mill table.

In this case, \( I = B \) and the radiation received at the detector is:

\[
V = \varepsilon \times B + I \times R
\]
\[
= (1 - R) \times B + R \times B
\]
\[
= B
\]

The energy level “seen” by the thermometer is equivalent to that of a
blackbody. This should be no surprise since the system is now a black
body enclosure. Hence, no correction for emissivity is required.

**A HOT BODY IN EVEN HOTTER SURROUNDINGS**

This could be, for example, measurement of a steel target 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 the most difficult case and
special consideration to the measurement solution must be made. It may
be possible to screen off the ambient radiation by fitting the thermometer
with a water-cooled sighting tube. Another method is to determine the
magnitude 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.

The system illustrated in Figure 16 shows a 3.9µm radiation thermometer used as part of a two-sensor system to provide background compensation for the stock temperature.

The 3.9µm thermometer is employed due to its ability to minimise effects of background reflection with the additional benefit of operating in a window where furnace gasses are transparent.
A second sensor, such as a thermocouple, measures background temperature. Both outputs are then supplied to a signal conditioning processor. The processor can calculate the value of product reflectivity from the emissivity setting. Since we now know the values of reflectivity and background temperature, the processor can calculate the true load temperature, corrected for background radiation.

Figure 17 shows why a 3.9µm is preferred to a shorter 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 the same conditions, the 3.9µm thermometer would read 844°C.
The 3.9µm thermometer is more able to cope with reflected radiation from hot furnace walls than a shorter wavelength thermometer. It can also be seen from the graph 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 shielding not the thermometer.

![Figure 18: Infrared Energy from Other Sources](image)
The Radiation Thermometer

TYPES OF THERMOMETER

Radiation thermometers can be grouped in several types:

**Broad Band**

The spectral sensitivity is not purposely limited: it depends on the detector, lens and window materials. This gives the capability of measuring low temperatures with a wide temperature span.

**Short Wavelength**

The spectral sensitivity is restricted, by choice of detector and/or optical filter, to the shortest wavelengths at which sufficient energy is emitted to generate a measurable detector output. This gives a high “slope” ie output versus temperature characteristic, which minimises the temperature error due to a given output error.

**Selected Waveband**

The spectral sensitivity is restricted by the choice of filter to the desired band. For example 4.8 to 5.2µm to measure glass surface temperature: at these wavelengths, the glass is almost completely opaque.
Ratio

Consists of two detectors using the same optical system but sensitive to two different wavelength bands. The ratio of the two detector outputs is a function of the surface temperature and is independent of both emissivity and absorption in the sighting path, provided these are the same for both channels.

In practice, the attractive feature of independence on surface emissivity is often nullified by the fact that emissivity is usually different in the two wavelength bands, and even small differences can lead to comparatively large temperature errors. See Chapter 6 for a more detailed discussion of the Ratio Thermometer and their applications.

Emissivity Enhancement (Surface)

A gold-plated reflector is placed on (or near) the surface of a target. As gold is a near-perfect reflector, an “enclosure” will be formed whose walls are either the surface, or a near-perfect reflection of the surface: this is a close approximation to a blackbody enclosure. A small hole in the reflector allows this radiation to fall on a detector whose output is nearly independent of the surface emissivity and depends only on the surface temperature. A correction can be applied to compensate for gold not being a perfect reflector. For surfaces with emissivities between 0.6 and 1.0, the correction is small and often negligible.

CONSTRUCTION OF A RADIATION THERMOMETER

The construction of the radiation thermometer can be split into several sections: an optical system which defines the angular field of view of the thermometer; a detector which converts the incident infrared radiation into an electric signal; an amplifier and signal processing circuit, usually where the emissivity compensation is performed; and a housing of suitable construction for the desired application. A schematic of a typical radiation thermometer is shown in Figure 19.
As stated above, the optical system defines the angular field of view of the thermometer, which in turn determines the minimum size of hot object (target size) that can be measured. 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.

**DETECTORS**

The detector defines the speed of response. It may define, or help to define the spectral response, but for a detector such as the thermopile, which is responsive to all wavelengths, the spectral response is defined by the optical system.

Detectors can be split into two main types: 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 through 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 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, however this is very often sufficiently fast.
Figure 20 shows the spectral response achieved by the difference detector materials.

![Figure 20: Detectors](image.png)

**Photon Detectors**

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 pn junction (photovoltaic mode). The detectors used in Land thermometers work in the photovoltaic mode. 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.

**Thermopiles**

Thermopiles are constructed from discrete elementary thermocouples, a number of these being connected in series to augment the output. The metals are vapour deposited on a very thin substrate with techniques first developed of Silicon Wafer manufacture. The junctions are blackened before use to improve absorption of radiation. Response times are of the order of 100ms.
**Pyro-electric**

Pyro-electric detectors consist of a strip of material which when heated by the incoming radiation, produce 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.

**THE THERMOMETER OPTICAL SYSTEM**

The optical system of a radiation thermometer comprises a lens, often with a second auxiliary 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 intersection of the field of view with the target 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.

Figure 21 shows a thermometer and its field of view. The diagram shows the sizes of target required at various distances. The instrument focus is at 500mm, where a target size of at least 5mm is required here to ensure the field of view is completely filled. The instrument may be used to measure a target at say 300mm, provided it is at least 9mm in diameter to ensure the field of view is filled.

![Figure 21: Example of Fixed Focus Thermometer Field of View](image)
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 field of view (FOV) of 100:1 and is focused at 1000mm, the target size at focus will be 1000/100 = 10mm.

Land provides tables of target size values at various distances from the optical datum on the instrument on the data sheets and operation manuals for each instrument variant. This enables the user to ensure that the target area 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 aberrations (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 some distance, say 1200mm, but it can be used at any distance, provided the target is sufficiently large (or small), and there is no obscuration between the thermometer and the target to reduce the incident energy.

Only a small amount of infrared radiation from the target will reach the detector – there are two main reasons for this: atmospheric absorption and the inverse square law.

- Atmospheric absorption effects can be overcome by careful selection of the operational wavelength of the thermometer.
- The Inverse Square Law: Radiation from a point diverges in a radial manner with a spherical wave front. As the wave propagates out, the surface area increases and consequently, the radiation density decreases. The instrument’s optics collect energy from an area defined by the field of view such that as the thermometer is moved away from the target, it receives energy from an increasingly large area, which exactly compensates for the energy decrease caused by the inverse square law.
For a fixed focus thermometer, in order to calculate the target size at any distance we need just 3 factors:

- The active lens diameter $L$ of the thermometer;
- The focusing distance $V$ of the thermometer;
- 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 be obtained from the target size table. $L$ can be obtained from the target size table at zero distance.

Figure 22 shows the field of view of a fixed focus instrument. The equations to calculate the target size at a distance $D$ from the thermometer are as follows:

Up to focusing distance, $V$:

$$\text{Target Size} = \frac{(T - L) \times D}{V} + L$$

Beyond focusing distance, $V$:

$$\text{Target Size} = \frac{(T + L) \times D}{V} - L$$

If we have a thermometer with a lens diameter of 35mm, focused at 600mm and a target size at focus of 30mm, viewing a target at a distance of 1200mm, the target size would be given by:
\[
\text{target size} = \frac{(30 + 35)}{600} \times 1200 - 35 = 95\text{mm}
\]

Land’s System 4 thermometers have adjustable focus and a through-the-lens 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 instrument 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.

For instruments which have variable focus, a standard range of adjustment is 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.

\[
d = \frac{s}{\text{FOV}}
\]

- \(d\) = Target Size, m
- \(s\) = Target Distance, m
- \(\text{FOV}\) = Field of View of thermometer

**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\(\mu\)m the optical system must be able to transmit this range of wavelengths. If the optical components of this instrument were made of optical crown glass, then the thermometer would not be able to see the target correctly. Figure 23 shows a list of optical materials along with their transmission range.
CALIBRATION OF INFRARED THERMOMETERS

As previously stated, blackbody radiation exists in any enclosure whose walls are at a uniform temperature. The radiation level is defined by the temperature only (by Planck’s Law): it is independent of the shape and size of the enclosure and wall material. It is therefore an ideal source to use for calibration of infrared thermometers.

We make a small hole in the surroundings – “small” being defined as less than 5% of the wall area. The presence of this small hole has only a negligible effect on the black body nature of the enclosure – it is a very close approximation to blackbody radiation.

The shape of the enclosure is commonly, as shown, a sphere or cylinder. Heating is by one or more electrically heated coils and the temperature is controlled from a thermocouple immersed in the cavity. The temperature is measured by a thermocouple placed as near as possible to the portion of the cavity that is viewed through the hole.
When used as a primary source a “furnace correction” is applied to the apparent temperature (derived from the thermocouple output) which corrects for thermocouple error and for the enclosure being not quite a black body.

For the most accurate work the furnace is used as a transfer between the thermometer being calibrated and a standard thermometer. Standard thermometers have proved to be stable over a period of several years. In this use there is no need to measure furnace temperature except to ensure that its temperature is steady.
The Ratio Thermometer

THE NEED FOR DUAL WAVELENGTH DETECTORS

Most infrared thermometers are single channel devices. This means that the energy from the target is focused onto a single detector. In order to return an accurate measurement, these thermometers need to see a full target. If the target is under the specified spot size, then the thermometer will also see some of the background and will tend to report a measurement that lies somewhere between the target and background temperature. The Thermometer can, of course, 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 (also known as a Two-Colour Thermometer) was developed to eliminate some of the problems associated with making temperature measurements using single channel instruments.

The Ratio Thermometer is a dual channel device - the optical system focuses the energy on to a dual element detector via an achromatic doublet lens. The outputs from both of the detectors is amplified and then the ratio of the two signals is produced. This ratio value is a function of target temperature (Figure 24).

Figure 24: The Ratio Thermometer
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 affected equally and the ratio of their output signals will remain unchanged.

**Optical system**

The optical system focuses infrared energy onto two detectors which are operational at different wavelengths. The amount of refraction of infrared energy as it passes through the optical material of a simple single lens is wavelength dependent – infrared energy of different wavelengths is focused by a different amount at each wavelength. This effect is known as chromatic aberration. Since the Ratio Thermometer operates at two wavelengths the apparent target size presented at one detector is larger than the other due this chromatic aberration effect. Therefore, an achromatic doublet lens is used to ensure good target size matching at the two operating wavelengths.

**Detector**

The detector used within a high temperature ratio thermometer is typically a tandem silicon cell device operating at wavelengths around 1µm. The detector is maintained at a constant temperature to ensure minimal change with varying ambient temperatures.

**THE TURN DOWN FACTOR**

A ratio thermometer will still indicate the correct temperature even when the target area is partially filled or obscured. The actual amount to which this area can be reduced is determined by the thermometer turn down factor. If the target area is so small, or so obscured, that insufficient energy is present to make a reliable measurement, the thermometer will generate an alarm and send the output either to maximum value or minimum value depending on user preference.

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.
Figure 25 shows a graph of energy emitted by a heated target across a portion of the infrared spectrum. The upper trace (red) shows the ratio output with a target at 1400°C which completely fills the thermometer field of view (100% energy received). The lower trace (orange) shows the output when observing the same target at 1400°C which now does not fill the field of view, or is the same size as above, but there are obstructions in the sight path (10% energy received). As can be seen, even though the energy from the target has been reduced significantly, the ratio between the energy received at the two wavelengths remains unchanged. 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 affected equally and the ratio signal remains unchanged.

A ratio thermometer will still read correctly even though the target area is reduced. The value of this reduction is determined by the turn down factor (normally expressed as a percentage) and the target emissivity. For a standard ratio thermometer, the turn down factor will remain constant at a value of around 5% for temperatures from 1700°C down to 900°C. When viewing a blackbody, a turn down factor of 5% means that the size of target area could be reduced down to an absolute minimum value of 5% of the thermometer spot size. If the target area was less than 5% the thermometer would assume that the target was so obscured that insufficient energy was present to make a reliable measurement. The ratio thermometer will generate an alarm when the thermometer is in “turn down” and send the output either to maximum value or minimum value.
depending on customer preference. At lower temperatures, for example 700°C, the turndown factor is a much lower value of 50%. This means that the size of area filling the field of view of the thermometer could be anywhere between 100% to down to an absolute minimum of 50%. Under these circumstances if the field of view of the thermometer is less than 50% filled, the thermometer will go into “turn down”.

The minimum target area for a ratio thermometer will change with target emissivity. If for example a ratio thermometer had a turn down factor of 5% when viewing a black body, the minimum target area could be as small as 5%. If the emissivity of the target were to drop to 0.1, the minimum possible target area would then have to be to 50%.

\[
\text{minimum area of FOV} = \frac{\text{Turn Down Factor}}{\varepsilon}
\]

It must be understood that the ability of ratio thermometers to operate with partially filled fields of view will be severely reduced when viewing low emissivity targets.

In should be noted that in applications where a ratio thermometer is viewing a target and the background is at a similar temperature, a potential problem exists. For example, if the intended target had a true temperature of 800°C and filled 50% of the field of view of the thermometer, and the remaining 50% was filled with a background at a uniform temperature of 700°C, the reported output from the ratio thermometer would be 779°C. At lower background temperatures, the background contribution is very small (even though the amount of filling may be large) and the errors are insignificant. It is important to understand that a ratio thermometer will not “pick” the highest temperature it can “see”, instead it will report a kind of average, in the same way a single wavelength thermometer would.

**EMISSIONS 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 - as a result there are two values of emissivity to consider as follows.

Single Wavelength Thermometer:

\[ S = \varepsilon F(T) \]

Dual Wavelength Thermometer:

\[ S = \frac{\varepsilon_1 F(T)}{\varepsilon_2 F(T)} \]

A material whose 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 materials are rarely the same at two different wavelengths and the actual ratio of the emissivities at both wavelengths is referred to as the non-greyness value.

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 method of evaluating the error of a Ratio thermometer in the event of a change in non-greyness is to use the percent-per-degree 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 that the effective wavelength for a typical Ratio thermometer operating at, for example, 0.95µm and 1.05µm would be approximately 10µm.

The effective wavelength is evaluated from as:

\[
\frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} \quad \lambda_1, \lambda_2 = \text{the operational wavelengths of the ratio thermometer}
\]

Once we have the effective wavelength, we can again calculate the %/°C value for a target temperature of for example, 1000K.

\[
%/°C = 100 \times \frac{14388}{10 \times 1000} = 0.14
\]

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

\[
\text{measurement error} = \frac{\% \text{ error in non-greyness}}{%/°C}
\]

For the above 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%

\[
\text{measurement error} = \frac{-3.0}{0.14} = -21.43°C
\]

It is now interesting to compare the above result with a standard 1µm thermometer measuring the temperature of a target at 1000K. As
calculated in a previous section, a single wavelength thermometer at this temperature will have a %/°C value of 1.44. 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%.

\[
\text{measurement error} = \frac{-3.0}{1.44} = -2.08°C
\]

It can be clearly seen that even a small change in non-greyness can cause a large measurement error. It should be noted that the non-greyness control of a Ratio thermometer has to be a factor of approximately 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. In practice however, it is usual for non-greyness at the target to vary significantly less than emissivity.

Despite this effect 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.
Temperature Measurement and Transparent Materials

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 shows some common optical materials with their usable transmission and reflection loss per surface. When using a thermometer to look through a window, it is important to ensure that the operational wavelength of the thermometer falls within the usable transmission band of the window. It is also important that the target emissivity is adjusted due to the loss of energy across the window, enabling the thermometer to read the correct temperature.

<table>
<thead>
<tr>
<th>Optical Material</th>
<th>Usable Transmission Band</th>
<th>Reflection loss per surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Crown Glass</td>
<td>0.3 to 2.7µm</td>
<td>4.0%</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>0.3 to 3.5µm</td>
<td>3.5%</td>
</tr>
<tr>
<td>Calcium Fluoride</td>
<td>0.15 to 12µm</td>
<td>3.0%</td>
</tr>
<tr>
<td>Germanium</td>
<td>1.8 to 20µm</td>
<td>3 to 36%</td>
</tr>
<tr>
<td>Sapphire</td>
<td>0.2 to 5.5µm</td>
<td>7.0%</td>
</tr>
<tr>
<td>Zinc Sulphide</td>
<td>0.4 to 11.5µm</td>
<td>15.0%</td>
</tr>
</tbody>
</table>

The emissivity control on the thermometer should be set to compensate for target emissivity and window losses. For high temperature applications (where the target is much hotter than the thermometer), the following formula provides a good approximation to the required emissivity setting:
\[
\varepsilon_{\text{set}} = \varepsilon_{\text{target}} \times (1 - R_1) \times (1 - R_2) \times \tau_{\text{int}}
\]

Where \(\varepsilon_{\text{set}}\) is Emissivity set, \(\varepsilon_{\text{target}}\) is the target emissivity, \(R_1\) is the reflectivity of window surface 1 (as a fraction, e.g. 7\% = 0.07), \(R_2\) is the reflectivity of surface 2, and \(\tau_{\text{int}}\) is the internal transmission of the window.

In most cases, \(\tau_{\text{int}}\) is equal to 1 (the window doesn’t absorb any infrared energy), and \(R_1\) and \(R_2\) are equal, so the above equation simplifies to:

\[
\varepsilon_{\text{set}} = \varepsilon_{\text{target}} \times (1 - R)^3
\]

For example, if an M1 thermometer (waveband about 1\,\mu m) is viewing a target with emissivity of 0.8 through a sapphire window (7\% reflectance per surface), the emissivity should be set to:

\[
\varepsilon_{\text{set}} = 0.8 \times (1 - 0.07)^3 = 0.69
\]

Caution: If the window is very thick, or the material is not ideally suited to the thermometer waveband, the simplified equation may not yield the correct result, and it might be necessary to use the full formula given at the start. Additionally, this formula assumes that infrared energy emitted by the window, or reflected into the thermometer by the window is negligible. This is normally true when viewing high temperature targets. The assistance of the Design Department should be sought in situations where the target temperature is near or below ambient, or where the window temperature is close to that of the target. Care should also be exercised to ensure that the window cannot reflect radiation from a high temperature source directly into the thermometer.

**Transmission of Infrared through the Atmosphere**

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.

Figure 26 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 will absorb the infrared energy.

![Figure 26: Transmission of Infrared Through the Atmosphere](image)

The actual amount of absorption is dependent on path length and meteorological conditions. It is important that thermometers do not operate at wavelengths where there is an absorption band. Thermometers are designed to operate in “Infrared Windows”, where the transmission is very high. Such regions are 1µm, 1.6µm, 3.9µm, and 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.

**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.

As previously stated, if $a$, $r$, and $t$ are the object’s fractional values of absorption, reflection and transmission then:
\[ a + r + t = 1 \]

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

\[
S = a \times F(T) + r \times F(T_b) + t \times F(T_r)
\]

\( T \) = Target Temperature, K
\( T_b \) = Background Temperature, K
\( T_r \) = Foreground Temperature, K

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

It can be seen from the Figure 27 that 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 absorption and hence emissivity must increase as the transmission decreases.

![Figure 27: Semi-Transparent Targets](image)

Figure 28 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.
When selecting a suitable thermometer to measure a semi-transparent target, we must be sure of two points:

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

Two very common applications involving measurement of semi-transparent targets are in the manufacture and processing of glass and thin film plastics.

**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. It is possible to use a short wavelength thermometer where the glass is quite deep and hence has high absorption in the canal section of the Float Line process. Maximum absorption occurs at the longer wavelength and hence for successful measurement of float glass, a longer wavelength thermometer is required. Observation of Figure 29 shows 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.

![Figure 29: Glass Thermometer](image)

The Land 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 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.

**Thermometers for the Measurement of Plastic**

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. Even at moderate thicknesses, these are often opaque over large parts of the infrared spectrum and are therefore easily measured using traditional low temperature wide band thermometers.
Thin plastic films have a transmission (and hence emissivity) which is strongly wavelength dependent. The figure below clearly shows how a thin sample of plastic is highly transparent over much of the infrared spectrum. In this case, a broadband thermometer will “see” through the sample and will tend to measure whatever is behind it.

Figure 30 clearly shows a region around 3.4µm where the sample is extremely 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.

![Figure 30: Plastic Film Transmission](image)

Measurement of temperature of these types of plastic film is often possible if the thermometer is operational at a wavelength 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.

Figure 31 shows, in detail, the “3.43µm” opaque region for polypropylene at 0.02mm (20µm) thickness. The thermometer spectral response, shown in red, is perfectly located on the region of highest absorption, and is restricted to only this region, thereby minimising transmission and maximising emissivity.
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 fluorocarbons are not so opaque at 3.43µm and a better result can be obtained at 7.9µm.

**Emissivity of Semi-Transparent Materials**

The transmission and the reflection from the surface of an object will limit the emissivity of any semi-transparent target. For most hydrocarbon plastics, the reflection coefficient is 0.04 per surface. This sets an upper limit of 0.96 for the emissivity, even when it is 100% opaque. The emissivity value will fall with reducing thickness of the plastic film, leading to an increase in transmission from any infrared sources behind the target. It is useful to specify a minimum thickness for a particular plastic material to ensure reliable temperature measurement results.

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.

<table>
<thead>
<tr>
<th>Material</th>
<th>3.43µm Thermometer (mm)</th>
<th>8-14µm Thermometer (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>0.02</td>
<td>2.60</td>
</tr>
<tr>
<td>PVC</td>
<td>0.10</td>
<td>0.38</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.02</td>
<td>2.60</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Cellulose Acetate</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Acrylics</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td>Nylons</td>
<td>0.04</td>
<td>0.25</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.30</td>
<td>0.13</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.08</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Low Temperature Measurement

When an infrared thermometer is used to measure a low temperature (below 40°C) there are several factors which must be taken into consideration.

Although the target is hot and will radiate infrared energy, it should be understood that the detector inside the instrument will be at ambient temperature and will also be 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 (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 ambient conditions. To overcome this difficulty, the temperature of the detector is measured using an internal sensor and this value is compensated for in the thermometers signal processing stage.
When measuring higher temperatures (above 200°C), the effect of the energy radiated by the detector is very small and is disregarded.

**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. There are three components to consider.

- The energy radiated out of the thermometer detector, $D$. As previously discussed, when the temperature of the detector $T_d$ 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”.
- The energy radiated from the target due to target temperature $S$.
- 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

A number of signal processing stages must be performed before a reliable temperature measurement can be reported.

The energy radiated from the detector must be compensated for. This performed by measuring the temperature of the detector and then adding it to the output of the detector.

Background reflections must also be compensated for. The magnitude of the reflected component is dependent upon background temperature and reflectivity of the target surface. The signal processing system uses the emissivity setting on the thermometer to obtain a value of reflectivity \( r = 1 - \varepsilon \) 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 detector temperature, however there is a background temperature adjustment on some models.

The signal will then require emissivity compensation and linearisation.

In order to provide a usable measurement, there are a range of signal processing functions available which make the temperature output suitable for direct process control. There are three main types; Averager, Peak Picker and Track & Hold.
**AVERAGER FUNCTION**

The averager time function is used to smooth out any unwanted variations in the process variable signal. An averager may be used to ensure smooth, gradual changes in the output even though a rapidly fluctuating thermometer signal is present at the processor.

The averager time constant is adjustable. The effect of increasing the time constant is similar to increasing the damping.

![Averager Function](image)

*Figure 32: Averager Function*

**PEAK PICKER FUNCTION**

Peak pickers are used extensively on systems which are taking temperature measurements of intermittent targets such as falling glass gobs, hot material moving on conveying systems or hot steel products with surface scale. Quite often, rolled or continuously cast steel products are covered with patches of dark scale. The scale surface is usually at a lower temperature than the metal. The areas of high temperature metal and low temperature scale cause fluctuations of the measurement as they pass under the thermometer.

The peak picker allows the signal to rise instantaneously to the peak and then decay slowly to the arrival of the next higher level of temperature.

Figure 33 shows a representation of the output from a thermometer measuring hot material transported by a bucket conveyer system. The
thermometer is being used to monitor the temperature of the hot product and as an input to trigger a cooling system. The thermometer sees not only the hot product but also the much cooler sides of the buckets as they pass through the field of view of the thermometer.

The output of the thermometer is rather like a saw tooth wave, but the form of the output can be improved by using a peak picking system.

Signal decay from the detected peak is user adjustable to allow the system to follow progressively cooler peaks.

![Figure 33: Peak Picker Function](image)

**TRACK & HOLD**

The track and hold time function enables control of the output by an external command signal.

With the external command signal at high level the processor is in track mode with output as normal. When the external command signal is at low level the output is locked regardless of the input level. The output will remain held until the command signal returns to high level.

Track and hold is a useful feature where it is required to measure the temperature of the target for the duration of a very specific period of time in the process.
Figure 34: Track & Hold Function
Summary

In these Training Notes, we have covered the basics of Infrared Theory and related it to temperature measurement, defining such terms as Blackbody, Emissivity, and Reflectivity.

Using these principles, we have defined Radiation Thermometers and the method used to return a temperature measurement.

It has also been shown that different types of Radiation Thermometer are required for specific applications. These depend upon process conditions - an overview is shown below.

**TYPES OF RADIATION THERMOMETERS**

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

**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 250°C.

**Selected Waveband**

Selected Waveband Thermometers are usually application specific, which have been designed to overcome special application problems.
Examples of these are 4.8 to 5.2\(\mu\)m thermometer for glass surface measurement and 3.43\(\mu\)m thermometer for thin film plastic measurement.

**Short Wavelength**

These are usually thermometers which operate below 2.5\(\mu\)m. A typical example of this is a 1\(\mu\)m thermometer, used at high temperatures 600 to 1300\(^\circ\)C. These thermometers are good at minimising the effect of variable emissivity and are found throughout the steel and other high temperature industries.

**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.

**Application Dedicated Thermometers**

There are many other Application Dedicated Thermometers 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, will need to be known.

**LAND TRAINING SCHOOL**

For further information, or to book an Infrared Training Course, please contact the Dronfield Office on the details given below.

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Technical Trainer

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Appendix 1

GLOSSARY

ABSOLUTE ZERO At absolute zero, all molecular movement stops. All actual temperatures are above absolute zero. Absolute zero would occur at -273.16°C, -459.69°F, or 0 Kelvin.

ABSORPTION (A) Ratio of radiant energy absorbed by a body to the corresponding absorption of a blackbody at the same temperature. Absorbance equals emissivity on bodies whose temperature is not changing. \( A = 1 - R - T \), where \( R \) is the reflectance and \( T \) is the transmittance.

ATMOSPHERIC WINDOWS Spectral radiation regions not absorbed by atmospheric gases. These windows are transparent to radiation at those wavelengths. The most obvious window is the visible light window.

BAND PASS FILTER An optical or detector filter which permits the passage of a narrow band of the total Spectrum. It excludes or is opaque to all other wavelengths.

BLACKBODY The perfect absorber of all radiant energy that strikes it. The blackbody is also a perfect emitter therefore, both its absorbance \( (A) \) and emissivity \( (\varepsilon) \) are unity. The blackbody radiates energy in predictable spectral distributions and intensities which are a function of the blackbody’s absolute temperature.
**BOLOMETER** Thermal detector which changes its electrical resistance as a function of the radiant energy striking it.

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

**ELECTROMAGNETIC SPECTRUM** The ordered series of all known types of electromagnetic radiation, arranged by wavelength ranging from the short cosmic rays through gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, microwaves, to the long wavelengths of radio energy.

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

**EMISSION ENHANCEMENT** Mechanically increasing the emissivity of a surface to near-blackbody conditions (using multiple reflection techniques).

**FAHRENHEIT** A temperature measurement scale which defines the ice point of water as 32°F and the boiling point of water as 212°F. Absolute zero is -459.7°F.

**FIELD OF VIEW (FOV)** Horizontal field of view of an infrared lens. Usually expressed as a distance/spot size ratio.

**FREQUENCY** A property of a wave that describes how many wave patterns or cycles passes by in a period of time. Frequency is often
measured in Hertz (Hz), where a wave with a frequency of 1 Hz will pass by at 1 cycle per second

**GREY BODY** This is an object having an emissivity, of less than unity, but this emissivity is constant at all wavelengths (over that part of the spectrum where the measurement takes place).

**INFRARED** The portion of the Electromagnetic Spectrum whose wavelength is longer than that of red light. Only the portion between 0.7 and 20 microns gives usable energy for radiation detectors.

**KELVIN** Thermodynamic temperature scale. Zero Kelvin is -273.16°C (Celsius) or -459.7°F (Fahrenheit).

**MICRON (µm)** .001 millimetres. 10,000 Angstrom units. A unit used to measure wavelengths of radiant energy.

**NOISE** The random fluctuations that are always associated with a measurement that is repeated many times over. These fluctuations do not represent any real sources of infrared radiation of target, but rather are caused by the imperfections of the system.

**NON-GREYNENESS** The ratio of emissivities for a Ratio Thermometer. This can take a value greater than, equal to, or less than unity and accounts for materials whose emissivity varies with wavelength.

**OPAQUE** Transmittance \((\tau)\) equals zero.

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

**RATIO PYROMETER** (Also known as Two-Colour Thermometer) Measures temperature as a function of the radiation ratio emitted around two narrow wavelength bands.
**REFLECTIVITY** \( (R) \) The percentage of the total radiation falling on a body which is directly reflected without entry. Reflectance is zero for a blackbody, and nearly 100 percent for a highly polished surface. \( R = 1 - A - T \), where \( A \) is the absorbance and \( T \) is the transmittance.

**SPECTRAL RESPONSE** The region of the infrared spectrum over which the infrared thermometer is sensitive.

**SPOT SIZE** The diameter of the area where the thermometer’s field of view intersects the target object.

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

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

**TWO-COLOUR THERMOMETER** See **RATIO PYROMETER**

**ULTRAVIOLET** Electromagnetic radiation at wavelengths shorter than the violet end of visible light

**VISIBLE LIGHT** Electromagnetic radiation at wavelengths which the human eye can see.

**WAVELENGTH** The length of distance between cycles on a repetitive event.

**WIDE-BAND (TOTAL) PYROMETER** A radiation thermometer that measures the total power density emitted by the material of interest over a wide range of wavelengths.
Appendix 2

SELECTION CRITERIA FOR FIXED INFRARED THERMOMETERS

Land has an extensive range of Infrared Non-Contact Temperature measurement solutions. Selection of the most suitable instrument for a given application is essential to obtain optimal measurement results.

Selection criteria for the thermometer can be broken down into the following categories:

- Process and Environmental Conditions
- Spot size, distance to target and temperature range
- Material and surface condition of target object
- Signal Processing and Interface

Process and Environmental Conditions

The first consideration should be that of the process type, the method of heating (e.g. oil fired, induction, etc) and where would the measurement take place (e.g. in furnace, on conveyer, at the rolling mill coiler).

The next stage is to decide on the most appropriate measurement system, either a fixed or portable system, spot thermometer, linescanner or thermal imager.

The temperature and nature of immediate surroundings will determine the level of protection hardware and instrument cooling required.
Another consideration is the sight path conditions (e.g. Clean and clear air, dust, fumes, steam, obstructed, products of combustion etc) as this will determine the air purge and sighting tube requirements of the system.

**Spot Size, Distance to Target and Temperature Range**

It is essential that the target object be greater in size than the diameter of the spot size of the thermometer. Installation limitations may require the thermometer to be mounted a set distance from the target. In this case divide the target distance by the required spot size to give the minimum spot size ratio.

e.g. 1000mm / 10mm = 100:1 FOV

Therefore selection of the thermometer should be restricted to instruments which can achieve or better this FOV.

For the required temperature range, select thermometers that meet the measurement point Max/Min/Normal. We will select the output range later...

Final selection of the exact model based on the other selection criteria will determine the output range of the thermometer, which would normally cover the max, min and normal operating temperatures.

**Material and Surface Condition of Target Object**

It is important to know the target material (e.g. steel ingot, molten glass, thin film plastic) in order to correctly select the operational wavelength of the thermometer. Normal practice is to use the shortest wavelength available for the required temperature range. As previously discussed, short wavelength thermometers are better able to cope with variable emissivity targets. However, there are some cases, such as measurement of glass and plastic, when specific wavelength thermometers should be employed.

The exact condition of the surface (e.g. bright unoxidised, heavily oxidised, painted, covered in scale) is also essential information, as this
will determine the emissivity of the target and if there is any level of variance.

**Signal Processing and Interface**

The last stage is to determine the signal processing and transmission requirements. There are a number of considerations when choosing the processor unit:

The type of display required
- None
- Digital read-out
- Analogue (chart)
- Bar graph

Alarms required
- None
- High and low
- High
- Low

Transmission protocol required
- RS232
- RS485

Preferred mounting for processor
- Panel mounted
- Din Rail mounted
“This Training Manual presents an introduction to infrared temperature measurement, giving a solid basis in the principles employed in the technique.

It allows the reader to obtain a fundamental understanding of how infrared thermometers make temperature measurement, using plain language to explain the principles of non-contact temperature measurement.

It is particularly suitable to newcomers to the field of temperature measurement by infrared.”