TEMPERATURE MEASUREMENT

by N. Asyiddin
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## TEMPERATURE MEASUREMENT

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Temperature is one of the most frequently used process measurements. Almost all chemical and petrochemical processes and reactions are temperature dependent. Not infrequently in chemical plant, temperature is the only indication of the progress of the process. Where the temperature is critical to the reaction, a considerable loss of product may result from incorrect temperatures. In some cases, loss of control of temperature can result in catastrophic plant failure with the attendant damage and possibly loss of life.

There are many other areas or industry where temperature measurement is essential. Such applications include steam raising and electricity generation, plastics manufacture and moldings, milk and dairy products and many other areas of food industries. Then, of course, where most of us are most aware of temperature is in the heating and air-conditioning systems which make so much difference to people’s personal comfort.

For the understanding of temperature measurement it is essential to have an appreciation of the concepts of temperature and other heat related phenomena. This includes deformation of temperature, heat, specific heat capacity, thermal conductivity, latent heat and thermal expansion.

Why we need to measure temperature?

- **Safety** :- To ensure that process temperature remains within the limits of plant design, so damage does not occur to columns, separator, piping and rotating equipment by exceeding their safety limits. For example carbon steel piping becomes brittle if it is cooled below minus 20 °C. It loses its mechanical strength if it is heated above 450 °C.

- **Quality** :- Providing a more uniform and predictable product quality under steady process conditions.

- **Control** :- To achieve correct control of process where temperature is a critical parameter. These temperature dependant process include distillation, metering and regeneration.

**What is temperature?**

Temperature is broadly defined as ‘degree of hotness or coldness of a body or an environment’. In a narrower sense, temperature is *the degree of hotness or coldness referenced to a specific scale*. It is a name for some condition in matter which determines the direction and extent of transfer of the kind of energy called ‘heat’.

Temperature is an expression denoting a physical condition of matter, just as are mass, dimensions and time. Heat is a form of energy associated with the activity of molecules of a substance. These minute particles of all matters are assumed to be in continuous motion which is sensed as heat. Temperature is a measure of this heat.
Units And Scales of Temperature

Temperature scales

The two fixed points for temperature scales are:

1. the lower fixed point or ice point – which is the temperature of ice, prepared from distilled water, when melting under a pressure of 760 mmHg (or 1 atm, or 101.325 kPa, or 14.67 psi). The pressure of the atmosphere does not have a great influence on the melting point, but the ice should be in the form of fine shavings and mixed with ice-cold water. For the ice point, is the temperature at which water and ice can exist together.

2. the upper fixed point, or steam point – which is the temperature of steam from pure distilled water boiling point under a pressure of 760 mmHg in latitude 45°.

The boiling point, $t_p$ of water at a pressure, $p$ mmHg is given by the formula;

\[
t_p = 100 + 0.0367 (p - 760) - (p - 760)^2 \degree C
\]

Temperature scales development

Galileo invented the liquid in glass thermometer around 1592 in crude form. Isaac Newton (1642-1727) first suggested fixed points of reference between freezing water and boiling water. Danish astronomer, Ole Roemer (1644-1710) had an obscure scale based on the number 60, with fixed points including human body temperature (at 28°C instead of the correct 37°C) and salted ice and water. He was first to use alcohol in his open thermometers.

A more well-known scale is by dutchman Daniel Gabriel Fahrenheit (°F) who observed the work of Roemer, used alcohol but improved it by sealing the tops of his thermometers. Alcohol has a few problems with its high expansion factor and it can cling to the tubes, so Fahrenheit started to use Mercury.

He then redesigned the thermometer by compensating for the low expansion factor by using a bulb at the bottom of the tube with a smaller interior bore. By 1714, he had produced a mercury in glass thermometer vastly superior to anything before, the design of which has hardly altered to this day.

The odd scale 32°F for freezing water and 212°F for boiling water was because of his trying to improve on the scale of Mr Roemer. North America still uses this scale. He also discovered that water boils at different temperatures depending on the atmospheric pressure.

Another scale was by the frenchman Rene Ferchaunt Reaumur (°R) was based on the number 80. Freezing water was 0°R and boiling water was 80°R at 1 atmosphere. He used an alcohol/water mixture, and was the first to use the standards of freezing and boiling of water as his sole points. This scale was widely used in Germany and France.

Mr. Anders Celsius (°C) of Sweden by 1742 had the 100° scale thermometer which we use today, except for one major difference; it was upside-down. He used 100°C as “ice point” and 0°C as boiling point. A frechman, Christin, had developed a 100° scale the correct way up, at the same time. In 1750, after Celsius sudden death, the scale was reversed and named after him anyway. It was named for a long time “Centigrade”, meaning hundredth degree, until after 1940.
Lord Kelvin (°K) a British thermodynamicist, named the absolute unit “Kelvin” (derived from the Celsius). The absolute scale Rankine was derived from the Fahrenheit scale.

The Kelvin is the SI unit of temperature - abbreviation as “K” without any degree sign (°).

The degree of both scales is equal to \( \frac{1}{273.16} \) of the temperature interval between absolute zero and the triple point of water.

**Triple Point**

The triple point of water, is simply a temperature/pressure combination where the states of ice, water, and water vapour can exist together. Both a solid and a liquid phase usually exist together; with a certain amount of vapour (may or may not be visible) depending on the temperature and pressure. The triple point of water occurs at 0.01°C at pressure of 4.6 mmHg (or equivalent to 0.6132829 kPa, or 0.08894916 psi)

**Absolute Zero temperature**

Absolute zero temperature is a state where all molecular activity has ceased, it is the coldest state there is, at a temperature of –273.16°C, or 0 Kelvin. However, this temperature was determined by calculation (theoretical), up until now this temperature has not been attained.

**International Practical Temperature Scale of 1968 (I.P.T.S. - 68)**

Scales are constructed by referring to the IPTS. The scale is based on a number of fixed points which can be accurately reproduced. There are 12 basic points and a number of secondary points. It was established in 1968 by international commission and revised in 1990.

The defining fixed points are established by realising specified equilibrium states between phases of pure substances. These equilibrium

The scale distinguishes between the International Practical Kelvin Temperature with the symbol \( T_{68} \) and the International Practical Temperature Scale with the symbol \( t_{68} \). The relationship between \( T_{68} \) and \( t_{68} \) is;

\[
t_{68} = T_{68} - 273.15 \text{ K}
\]

The size of the degree is the same on both scales being 1/273.16 of the temperature interval between absolute zero and the triple point of water (0.01°C). Thus, the interval between the ice point, 0°C and the boiling point of water, 100°C is still 100 Celsius degrees.

Temperatures below 273.15 K (0°C) are expressed in Kelvin (K), and in Celsius above 0°C.
<table>
<thead>
<tr>
<th>Equilibrium state</th>
<th>Assigned value of International Practical temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium between the solid, liquid and vapour phases of equilibrium hydrogen (triple point of equilibrium hydrogen)</td>
<td>$13.81$ $-259.34$</td>
</tr>
<tr>
<td>Equilibrium between the liquid and vapour and vapour phases of equilibrium hydrogen at a pressure of 33330.6 Nm$^{-2}$ ($\text{22/76}$ std. Atmosphere)</td>
<td>$17.042$ $-256.108$</td>
</tr>
<tr>
<td>Equilibrium between the liquid and vapour phases of equilibrium hydrogen (boiling point of equilibrium hydrogen)</td>
<td>$20.28$ $-252.87$</td>
</tr>
<tr>
<td>Equilibrium between the solid, liquid and vapour phases of oxygen (triple point of oxygen)</td>
<td>$54.361$ $-218.789$</td>
</tr>
<tr>
<td>Equilibrium between the liquid and vapour phases of oxygen (boiling point of oxygen)</td>
<td>$90.188$ $-182.962$</td>
</tr>
<tr>
<td>Equilibrium between the solid, liquid and vapour phases of water (triple point of water)</td>
<td>$273.16$ $0.01$</td>
</tr>
<tr>
<td>Equilibrium between the liquid and vapour phases of water (boiling point of water)</td>
<td>$373.15$ $100$</td>
</tr>
<tr>
<td>Equilibrium between the solid and liquid phases of zine (freezing point of zine)</td>
<td>$692.73$ $419.58$</td>
</tr>
<tr>
<td>Equilibrium between the solid and liquid phases of silver (freezing point of silver)</td>
<td>$1235.08$ $961.93$</td>
</tr>
<tr>
<td>Equilibrium between the solid and liquid phases of gold (freezing point of gold)</td>
<td>$1337.58$ $1064.43$</td>
</tr>
<tr>
<td>Triple point of normal hydrogen</td>
<td>$13.956$ $-259.194$</td>
</tr>
<tr>
<td>Sublimation point of carbon dioxide</td>
<td>$194.674$ $-74.476$</td>
</tr>
<tr>
<td>Freezing point of mercury</td>
<td>$234.288$ $-38.862$</td>
</tr>
<tr>
<td>Equilibrium between ice and air saturated water (ice point)</td>
<td>$273.15$ $0$</td>
</tr>
<tr>
<td>Freezing point of indium</td>
<td>$429.78$ $156.634$</td>
</tr>
<tr>
<td>Freezing point of bismuth</td>
<td>$544.592$ $271.442$</td>
</tr>
<tr>
<td>Freezing point of lead</td>
<td>$600.652$ $327.502$</td>
</tr>
<tr>
<td>Freezing point of antimony</td>
<td>$903.87$ $630.74$</td>
</tr>
<tr>
<td>Freezing point of aluminium</td>
<td>$933.52$ $660.37$</td>
</tr>
<tr>
<td>Freezing point of copper</td>
<td>$1357.6$ $1084.5$</td>
</tr>
<tr>
<td>Freezing point of nickel</td>
<td>$1728$ $1455$</td>
</tr>
<tr>
<td>Freezing point of palladium</td>
<td>$1827$ $1554$</td>
</tr>
<tr>
<td>Freezing point of platinum</td>
<td>$2045$ $1722$</td>
</tr>
<tr>
<td>Freezing point of rhodium</td>
<td>$2236$ $1963$</td>
</tr>
<tr>
<td>Freezing point of iridium</td>
<td>$2720$ $2447$</td>
</tr>
<tr>
<td>Melting point of tungsten</td>
<td>$3660$ $3387$</td>
</tr>
</tbody>
</table>
### Summary: 5 arbitrary scales are used to measure temperature

#### Conversions between Units

The 2 practical temperature scales in general use today are Fahrenheit Scale (°F), and Celsius Scale (°C).

To convert between the two scales, follow the following formula:

\[ °C = \frac{5}{9} (°F - 32) \]

\[ °F = \left(\frac{9}{5} × °C\right) + 32 \]

**Example:**

To convert 215°C to °F

\[
215°C = \left(\frac{9}{5} × 215\right) + 32 \°F \\
= (9 × 43) + 32 \°F \\
= 419°F
\]

To convert 300°F to °C

\[
300°F = \frac{5}{9} × (300 - 32) \°C \\
= \frac{5}{9} × 268 \°C \\
= 148.89°C
\]
HOW DID WE GET THE FORMULA?

CELSIUS AND FAHRENHEIT

Given that freezing point of water is 0 °C, and in Fahrenheit, it is 32 °F. The boiling point of water is at 100 °C, or at 212 °F.

Hence, we can write that:

\[
0^\circ C = 32^\circ F \quad \text{and,} \quad 100^\circ C = 212^\circ F
\]

Since the relationship is linear, we can plot a graph °F vs. °C as in the right;

Mathematically, a linear relationship can be written in the form of

\[y = mx + c\]

where \(y\) = y-axis variable (°F), \(x\) = x-axis variable (°C), \(m\) = slope of the graph, and \(c\) = where the graph cuts the y-axis.

The slope, \(m\), is given as:

\[
m = \frac{y_1 - y_2}{x_1 - x_2}
\]

The relationship is derived as follow;

\[^\circ F = m(^\circ C) + c\]

From the graph, we can see that,

\[c = 32\]

\[
m = \frac{212 - 32}{100 - 0} = \frac{180}{100} = \frac{9}{5}
\]

Therefore, we have the relationship as;

\[^\circ F = \frac{9}{5}(^\circ C) + 32\quad \text{, and thus,} \]

\[^\circ C = \frac{5}{9}(^\circ F - 32)\]
**KELVIN AND RANKINE**

From earlier discussion, we know that the Kelvin unit is based from Celsius scale but the referral point is from the absolute zero. The Kelvin unit is produced based on calculation, i.e. it is theoretical, because absolute zero is 'impossible' to this world.

We are given that:

\[
0 \text{ °C} = 273.16 \text{ K} , \text{ and, } 100 \text{ °C} = 373.16 \text{ K}
\]

The linear relationship is plotted as in the right;

Similar with Celsius and Fahrenheit case, the relationship is derived as follow;

\[
K = m(°C) + c
\]

From the graph, we can see that,

\[
c = 273.16
\]

\[
m = \frac{373.16 - 273.16}{100 - 0} = \frac{100}{100} = 1
\]

Therefore, we have the relationship as; \( K = (°C) + 273.16 \), and thus, \( °C = K - 273.16 \)

The Rankine unit is based from Fahrenheit scale but referred to absolute zero. The derivation is as follow;

\[
°F = m(°F) + c
\]

From the graph, we can see that,

\[
m = \frac{673.69 - 491.69}{212 - 32} = \frac{182}{180} = \frac{91}{90}
\]

and,

\[
c = \frac{90 \times °R}{91 \text{ °F}}
\]

by applying coordinate (212,673.69),

\[
c = \frac{60632.1}{19292}
\]

Therefore, we have the relationship as;

\[
°F = \frac{91}{90}(°F) + \frac{60632.1}{19292}, \text{ and thus, } °F = \frac{90}{91}(°R - \frac{60632.1}{19292})
\]
Methods of Temperature Measurement
Heat cannot be measured directly, indirect approaches must be employed. Heat is only one form of energy, therefore it can be transferred or changed into other forms. If two bodies are at the same temperature, there is no exchange of heat.

Some of the ways in which temperature may be inferred by the changes it causes are;
1. change in volume (pressure, viscosity, density, etc.)
2. a change in the electrical resistance
3. the voltage created at the junction of two dissimilar metals
4. the resonant frequency of a crystal
5. variations in the susceptibility of a paramagnetic salt in a magnetic field
6. the rate at which events take place

Generally, temperature measuring methods can be divided into 2 categories;
A. Non-electrical systems
B. Electrical or Radiation systems

For expansion type of temperature sensor, observation that in a container (close-system), pressure and volume increase as temperature increase. The relationship between temperature, T, pressure, P, and Volume, V, can be expressed as;
\[ PV \propto T \]
\[ \therefore PV = kT, \text{ where } k \text{ is a constant.} \]

A. Non-electrical systems
The non-electrical systems are based on one of the following principles;
i. change in volume of liquid when its temperature is changed
ii. change in pressure of a gas when its temperature is changed
iii. change in vapour pressure when the temperature is changed
iv. change in dimensions of a solid when its temperature is changed

Liquid-in-glass Thermometers
Basic parts of a thermometer;
i. Bulb
ii. Stem
iii. Scale
iv. Liquid

The liquid-in-glass thermometer consists of a glass envelope, a responsive liquid, and indicating scale. The envelope is in two parts fused together, a bulb completely filled with the liquid and a capillary scale section containing the liquid in access of that required to fill the bulb. The position of the end of the capillary column or index serves, by prior calibration, to indicate the temperature of the bulb. The scale may be marked directly on the capillary tube as in the laboratory or clinical versions, or may be on a separate member mounted alongside the capillary tube as in the domestic and industrial forms.

Various liquids are used in liquid-in-glass thermometers. Mercury is the choice for higher temperatures or where accuracy is critical. Its advantages are a broad temperatures span between freezing and boiling points, a nearly linear coefficient of expansion, the
relative ease of obtaining it in a very pure state, and its non-wetting of glass characteristic. The disadvantages are cost, relatively low coefficient of expansion and readability characteristics.

For measurements below the freezing point of mercury (e.g. –39 °C), organic liquid such as toluene, aliphatic hydrocarbons, or organic phosphates are used. Advantages are low freezing point, superior readability to mercury when coloured with inert dyes, and lower cost. Disadvantages are lower boiling points, greater tendency to separate in the capillary, and wetting of glass characteristic.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>Mercury</td>
<td>–39 ~ 600</td>
</tr>
<tr>
<td>Mercury alloys</td>
<td>–60 ~ 120</td>
</tr>
<tr>
<td>Organic liquids</td>
<td>–200 ~ 230</td>
</tr>
</tbody>
</table>

The capillary above the liquid is generally filled with suitable gas. For the better grade thermometers, normally Dry Nitrogen is used. Air is often used in the less expensive mercury types as well as in the organic liquid-filled. Electric contact thermometers are generally filled with hydrogen. Maximum registering thermometers are sealed shut in a vacuous condition.

Glass thermometers are made up of 3 classes:
  i.  Class A
  ii. Class B
  iii. Class C
Filled System Thermometer

This system was built on the basis that all fluids (liquids, vapour or gases) expand when heated, contract when cooled. As the temperature of fluids changes, the volume also changes. This phenomena is utilised to expand a pressure element (usually bourdon element) which in turn positions an indicator or a transmitter coil or any other mechanism.

For example, see the following figure;

- A sensitive pressure bulb, immersed in the medium to be measured.
- A capillary tube, connecting the bulb to a readout or transmitting device.
- A pressure element actuating device, to respond to pressure changes caused by temperature.
- A linkage movement to effect indication, reading and transmission.

Filled system have been classified into 4 groups by Scientific Apparatus Makers Association (SAMA). The classes are;
- Class Ι – for liquid filled
- Class ΙΙ – for vapour filled
- Class ΙΙΙ – for gas filled
- Class ΙV – for mercury filled system

Class I and Class V use the Volumetric principle, while Class II and Class III use the Pressure principle. Our concern is in Class I and Class III because they are most commonly used in petrochemicals, chemicals, and oil & gas industries.
**Class I - liquid filled**

This liquid filled (mercury excluded) classification is subdivided into 3 groups:

1. **Class I** - uncompensated
2. **Class IA** - fully compensated (capillary and case)
3. **Class IB** - case compensated only

These systems operate on the principle that the temperature signal is generated by and proportional to a volume change in the bulb. They often are referred to as *liquid expansion type*.

Fill liquid chosen by the manufacturer are usually selected to give large expansions per degree change in temperature, thereby holding bulb size to a minimum. Pressure inside the system must exceed the vapour pressure of the fill liquid to prevent vaporization, and minimum temperature of the system should be kept above the freezing point of the fill liquid to prevent plastic deformation of the pressure element.

Bulb size varies inversely with the expansivity of the fill liquid and inversely with the span.

System reaction is linear, except at low temperature. Most major instrument manufacturers do not market Class I instrument; they do market however, Class IA and Class IB instruments. If the capillary length is short (10 ft or less), Class IB systems can be successfully used, since the bimetallic compensator normally used compensates for all or most of the capillary.

Speed of system response, generally around 5 to 10 seconds, is slow compared to other classes because of thermal mass. Respond speed can be increased by decreasing the bulb outside diameter. Along capillary with a small diameter is sometimes coiled to provide bulb capacity requirements within minimum space, sometimes coiled to provide bulb capacity requirements within minimum space, a practice used frequently for measuring temperature in large air handling system, such as building air conditioning systems. Capillary type bulbs used with Class I, III and V instruments can be left uncoiled to average the temperature over the entire bulb length.

**Maximum and Minimum Temperature and Range Spans**

The minimum temperature is limited to the freezing point of the organic liquid employed from approximately -75 to -200 °C, depending upon the liquid used. The maximum temperature to which the liquid is stable is approximately 300 °C. The minimum range span is determined by the maximum bulb size that is practical, generally 12 to 25 °C although spans as short as 5 °C are used. The maximum span sometimes is limited by nonlinearity of expansivity and compressibility of the fluid fill to approximately 150 °C, so that standard accuracy may be met with linear dials and charts. Some liquids, however, deliver a linear signal for spans as large as 250 °C. Mercury
filled thermal systems may be used between -38 and 650 °C. Organic liquids freeze at a much lower temperature and are commonly used between -75 and 300 °C. Because of the higher expansivity, organic filled systems are more adaptable to short spans while the lower compressibility of mercury makes it easier to use on long spans. In either case, the minimum span is usually limited by the largest practical bulb size.

**Capillary and Case Compensation**

The non-metallic liquid systems are particularly vulnerable to errors resulting from capillary temperature changes because of the high expansivity of the fill. Only if the capillary volume is very small can these errors be ignored and a Class IB system used. See figure 11.

To neutralize the capillary temperature error an auxiliary thermal system is employed. See figure 10.

The mercury filled system may be compensated fully by an alternate method. This employs a capillary containing Invar wire which can, by proper selection of dimensions, cancel any net volume change due to the expansion of the mercury. It should also be noted that, because of low expansivity of mercury, Class VB systems can have capillary up to 50 ft with good performance. A VA system using compensated capillary, an IB, or VB often is preferred to a Class IA because of the relative simplicity of the construction, lesser vulnerability to abuse, and lower cost. Since the bourdon volume changes with measured temperature changes, the case compensation can be perfect at only bulb temperature. In practice, this compensation is adjusted to a specified tolerance with the bulb at midrange. This results in the thermometer being slightly overcompensated at range bottom and slightly undercompensated at range top. Attention must be paid to these details if precise measurements are desired.

**Class II - liquid vapour system/vapour-pressure system**

Class II systems utilise the vapour pressure of a volatile fill liquid as a pressure source to actuate the element. The system pressure will always be that occurring at the liquid-vapour interface. No compensation is necessary in vapour-pressure type systems. Care must be taken during manufacture to have the fill liquid, bulb, capillary and case at the same temperature.

The are four subdivisions of this class;

1. **Class II A** :- designed for bulb placement in a process whose temperature always exceeds the case ambient temperature (figure 12).

2. **Class II B** :- designed for bulb placement in a process whose temperature is always below the case ambient temperature (figure 13).

3. **Class II C** :- designed for bulb placement in a process whose temperature can exist periodically both above and below case ambient temperature, but whose temperature near case ambient temperature is unimportant (figure 14).

4. **Class II D** :- designed for bulb placement in a process whose temperature measurement, when at case ambient is important, and which temperature can exist periodically both above and below ambient temperature (figure 15).

The fill fluid in a Class II A system is in a vapor state in the bulb and in a liquid state throughout the rest of the system (figure 12). The bulb must be sized to contain changes in volumes of the fill fluid in the bourdon, capillary and bulb due to ambient process temperature fluctuations while still maintaining the liquid-vapour interface within the bulb. Bulb length is therefore directly proportional to capillary length.
Long capillaries slow the response times of Class II systems. The time constant (time, in seconds, necessary for the system to register 63.2% of a step change) of a Class IIA system is approximately 1 second for a 10-foot capillary but is about 10 seconds for long capillaries. Spans vary from 40 °F to 300 °F generally, with range limits between ambient and 550 °F.

Class IIB systems have all of the fill liquid contained within the bulb and, therefore, are not affected by ambient conditions (Figure 13). Bulb volume is generally less than those for Class IIA systems.

Response times of Class IIB systems are essentially the same as for Class I systems.

Class IIB system spans vary from 40 °F to 300 °F generally, with range limits from ambient to about -430 °F.
Class IIC systems, which can measure temperature above and below ambient but not at ambient, are constructed and filled so that the liquid part of the fill fluid exists in the capillary and bourdon when the bulb temperature is greater than ambient (Figure 14). When bulb temperature drops below ambient, the fill transfers into bulb (Figure 14). During the transfer the location of the liquid-vapour interface is undefined; therefore, system pressure does not represent an analog of bulb temperature. Span and range limits essentially encompass those of Class IIA and Class IIB systems.

Bulb and instrument elevations must be virtually the same because of the fluid-vapor balance at the ambient crossover point. No compensation is available for elevation difference. Bulb volume is such that it will contain the volume of both capillary and bourdon and changes that occur in all portions of the system. It is usually larger than volume than volumes for Class IIA and Class IIB systems.

Response times are quite similar to Classes IIA and IIB. Transfer time when bulb temperature passes through ambient ranges from 5 minutes to an hour.

Class IID systems are constructed such that the volatile fill fluid is sealed in the bulb by a nonvolatile liquid which also acts as a transmitting medium between vapor pressure in the bulb and the bourdon mechanism (Figure 15).

Bulb size is usually the largest of all Class II systems due to the trap used to prevent the volatile fluid from ever reaching the capillary. The thermal mass of the trap itself and the use of the more viscous sealing fluid result in response times in the 5 to 10-second range.

**Maximum and Minimum Temperatures**

The maximum temperature is limited by the critical point of the liquid employed and by the tendency of the most known organic liquids to change chemically at 316 C or higher. The minimum temperature is generally limited to approximately -40 C because of loss in reading sensitivity at lower temperature coupled with the requirement that the bourdon must be able to withstand the vapour pressure of the liquid at room (or possible shipping) temperatures.

**Capillary and Case Compensation**

The capillary of Class II systems is insensitive to temperature changes. It is necessary, however, that the capillary temperature of Class IIA systems, when the capillary and bourdon are filled with actuating liquid, should not be at a point that exceeds the bulb temperature. The internally contained fluid or vapour within the bourdon is also insensitive to temperature changes as above. However, the modulus elasticity will decrease with increasing temperature, causing a shift of only 1.5 to 2% for a 56 °C case temperature change. In most uses, this effect is not important and no compensation is provided.
Class III - gas filled
This system is defined by SAMA as "a thermal system filled with a gas and operating on the principle of pressure change with temperature change". The system is usually compensated for ambient temperature effects in one of the two ways:
1. Class IIIA: With a second thermal system minus the bulb, or an equivalent means of compensation.
2. Class IIIB. With compensation means within the case only.

Maximum and Minimum Temperature and Range Spans
Gas thermal systems are able to cover the widest range of temperature of any of the filled systems. They are usually limited on the low side by the critical temperature of the gas used and on the high side of the bulb materials (commonly 5 K and 925 K). The maximum span is limited only by the above conditions of use and the nonlinearity due to mass flow from bulb. The minimum span is limited by the pressure at which the bourdon becomes overstressed. The gas system lends itself to use with a transducer with beading springs, making many more ranges, especially with short spans (25 K) available. Equation describes capillary temperature error in Class III system:

\[ E = \frac{100V_c \cdot \Delta T_c \cdot T_c^2}{(V_b T_c + V_c T_b)T_c R} \]

Where, \( T_c \) = mean capillary temperature, \(^\circ R\)
\( T_b \) = absolute temperature of bulb, \(^\circ R\)
\( \Delta T_c \) = capillary temperature change, \(^\circ F\)
\( R \) = span, \(^\circ F\)

The following table is the summary or Guideline data for filled systems.

<table>
<thead>
<tr>
<th>Filled System Classification (SAMA)</th>
<th>Fill Fluid</th>
<th>Compensation</th>
<th>Scale</th>
<th>Range Limits, °F</th>
<th>Overrange</th>
<th>Bulb Elevation Errors</th>
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<td>I</td>
<td>Liquid</td>
<td>Uncompensated</td>
<td>Linear Above −100°F</td>
<td>−125</td>
<td>600</td>
<td>100% Minor below 100 ft</td>
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<tr>
<td>IIA</td>
<td>Vapour</td>
<td>Not required</td>
<td>Scale divisions increase with temperature increase</td>
<td>−430 to Amb.</td>
<td>Amb. to 550</td>
<td>Almost always less than 100% Minor below 100 ft</td>
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<td>IIIB</td>
<td>Gas</td>
<td>Case</td>
<td>Linear Above −400°F</td>
<td>−400</td>
<td>1500</td>
<td>100 ~ 300%** None</td>
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<td>Case</td>
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<td>100 ~ 300%** None</td>
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<td>( SAMA has no Class IV )</td>
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<td>VA</td>
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<td>100% Minor below 25 ft</td>
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* depends on the bulb length
** depends on range
*** bulb and measuring element must be at the same elevation
**Bimetallic Element**

The bimetal thermometer, although widely used today, was not acceptable for industrial and laboratory use before about 1935. The fact that bimetal elements bend with temperature changes was observed over a century ago. These elements were then used for temperature correction in chronometers.

The term “thermostatic bimetal” is defined as a composite material, made up of 2 or more different metals fastened together, which, because of the different expansion rates of the components, tends to change its curvature when subjected to change in temperature.

There are 3 types of most commonly used in thermometers;
1. flat spiral
2. single helix
3. multiple helix

Bimetal strips are fabricated from 2 strips of different metals with different coefficients of thermal expansion, bonded together to form a cantilever. Typical metals are Invar and brass. See the following figure;
Thermometer with spiral Bimetallic elements.

Thermometer with Helical Bimetallic element

Helical formed Bimetallic strip allow rugged construction of small diameter thermometer

Gas-in-metal expansion thermometer
B. Electrical or Radiation systems

The electrical systems are based on one of the following principles;
1. the Seebeck Effect (thermocouples).
2. change in resistance of materials as their temperature is changed.
3. the radiated energy emitted by an object is a measure of its temperature.
4. the brightness of an object or the energy radiated at a particular wavelength (in the visible band) is a measure of its temperature.

Thermocouples

Thermocouple is made up of two dissimilar metal conductors joined at one end, usually called the hot or detecting junction, and connected to some emf measuring instrument at the cold end of the conductors.

Thermocouples development

Seebeck Effect – Thermo-electricity
In 1821, Seebeck discovered that if a closed circuit is formed of two metals, and the two junctions of the metals are at different temperatures, an electric current will flow round the circuit (i.e. voltage is induced).

Seebeck arranged a series of 35 metals in order of their thermo-electric properties. In a circuit made up of any two of the metals, the current flows across the hot junction from the earlier to the later metal of the series (a portion of this series is as follow);

Bi-Ni-Co-Pd-U-Cu-Mn-Ti-Hg-Pb-Sn-Cr-Mo-Rh-Ir-Au-Ag-Zn-W-Cd-Fe-As-Sn-Te

Peltier Effect
In 1934, Peltier discovered that when a current flows across the junction of two metals, heat is absorbed at the junction when the current flows in one direction, and liberated if the current is reversed. The amount of that heat liberated, or absorbed, is proportional to the quantity of electricity which crosses the junction, and the amount liberated, or absorbed, when unit current passes for a unit time is called the Peltier Coefficient.

The portion of the total emf of a thermocouple that exists because of a difference in potential a single section of wire or conductor having a temperature gradient is the Thomson emf.

Thermocouple wires are chosen so that they will produce a large emf that varies linearly with temperature. Ideally chosen thermocouple material should have;

i. the Thomson emfs of the two wires additive in the circuit
ii. Thomson emfs that vary directly with temperature
iii. Peltier emfs that develop potentials at the hot junction that are in the same direction as the Thomson emfs
iv. Peltier emfs that vary directly with temperature
v. Thermoelectric power as high as is possible
**Thermoelectric Laws**

Several phenomena have been discovered which are acceptable as thermoelectric laws:

1. The application of heat to a single homogeneous metal is in itself not capable of producing or sustaining an electric current therein.

2. The thermal emf developed when the junctions of two dissimilar homogeneous metals are kept at different temperatures are not affected by temperature gradients along the conductors.

3. In a circuit consisting of two dissimilar homogeneous metals having the two junctions at different temperatures, the emf developed will not be affected when a third homogeneous metal is made a part of the circuit, provided the temperatures of its two junctions are the same.

4. The thermal emf of any two homogeneous metals with respect to one another is the algebraic sum of their individual emfs with respect to a third homogeneous metal.

5. The thermal emf produced when a circuit of two homogeneous metals exist between a first temperature and a second, and the thermal emf produced when that same circuit exists between the second temperature and a third are algebraically equal to the thermal emf produced when the circuit exists between the first and third temperature.

6. The algebraic sum of the emfs produced in a circuit containing two or more thermocouples all at the same temperature is zero.

7. The overall emf of a circuit containing two thermocouples in unaffected by the addition of more thermocouples at the same temperature as any of the others.

Generation of an electromotive force by the application of heat to one of the junctions of two dissimilar metals is known as the ‘**Seebeck Effect**’. 

Temperature gradients do not generate emfs in a homogenous conductor.
A third metal does not affect the overall circuit emf as long as its junctions are at a common temperature.

The thermal emf of two metals with respect to one another is the algebraic sum of their individual emfs with respect to a third metal.
The thermal emf produced in circuits between $T_1$ and $T_2$ and between $T_2$ and $T_3$ are algebraically equal to the emf created in a similar circuit between $T_1$ and $T_3$.

Additional thermocouples at $T_1$ or $T_2$ do not affect the overall emf.

**Cold-junction compensation**

The emf developed by a thermocouple depends on the temperature of both the measuring and the rate reference junctions, and so the user, to determine temperature must know:

1. the calibration data for the thermocouple
2. the measured emf
3. the temperature of the junction

The calibration of the wire may be obtained from manufacturers who wire guaranteed to match reference curves for emf versus temperature within specified tolerances, or it may be obtained by direct calibration.
The reference tables are usually based on a reference-junction temperature of 0°C. In many applications, it is not practical to maintain the reference junction at the ice point; to the observed emf is added the emf that the thermocouple would develop if the reference junctions were at 0°C and the measuring junction were at the actual temperature of the reference junctions. The temperature of the reference junctions can be maintained at a value higher than room temperature by a small temperature-controlled oven. A constant correction to the measurement gives the true temperature.

In other instruments, the temperature of the reference junction is at the ambient temperature, with correction being provided by temperature-sensitive devices. Some galvanometer-actuated instruments use a bimetallic spiral attached to hairspring assembly which changes pointer position as ambient temperature changes. The reference junctions are located so that they are at the same temperature as the resistor.

| Hot Junction temperature (mV) – Reference junction (mV) = Meter Readout (mV) |
| Hot Junction temperature (mV) – Reference junction (°C) ≠ Temperature rise |

Thermocouple reference junctions can be formed using an ice bath (A), thermoelectric refrigeration (B), a bridge circuit (C), or heated ovens (D). See figures below;
Thermocouple circuits
Several thermocouple circuits are shown below. The indicating instruments may be any devices for measuring small dc emfs. The leads may be copper as in the Diagram C, provided that both junctions of the leads to the thermocouple are at the same known temperature. If this is not the case, it desirable to use thermocouple extension wire as in Diagram B. This wire is either of the same material as the thermocouple wire or of material having the same temperature-emf relation as the thermocouple wire over a limited range of temperature.

A. Single thermocouple circuit requiring no extension cable.

B. Single thermocouple circuit having the reference junction at the measuring instrument.

C. Single thermocouple circuit having the reference junctions at a distance from the measuring instrument.

D. Equivalent circuit for shorted thermocouple circuit.
E. Multiple thermocouple circuit having the reference junctions at distance from measuring instrument.
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<th>Temp. Range</th>
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<td>1.792 ~ 13.820 mV</td>
<td>600 ~ 1820°C</td>
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<tr>
<td>E</td>
<td>0 ~ 37.079 mV</td>
<td>0 ~ 2316°C</td>
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<tr>
<td>J</td>
<td>-9.719 ~ 76.370 mV</td>
<td>-250 ~ 1000°C</td>
</tr>
<tr>
<td>K</td>
<td>-8.096 ~ 69.555 mV</td>
<td>-210 ~ 1200°C</td>
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<tr>
<td>L</td>
<td>-5.891 ~ 54.886 mV</td>
<td>-50 ~ 900°C</td>
</tr>
<tr>
<td>N</td>
<td>-8.166 ~ 53.147 mV</td>
<td>-50 ~ 1300°C</td>
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<tr>
<td>R</td>
<td>-3.990 ~ 47.514 mV</td>
<td>-50 ~ 1372°C</td>
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<td>S</td>
<td>-0.101 ~ 21.089 mV</td>
<td>-50 ~ 1767°C</td>
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<td>T</td>
<td>-0.103 ~ 18.682 mV</td>
<td>-50 ~ 1767°C</td>
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<td>U</td>
<td>-6.181 ~ 20.873 mV</td>
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<td>+ve Leg</td>
<td>Pt–6% Rh (Tungsten–6% Rhodium)</td>
<td>-5.693 ~ 34.320 mV</td>
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<td>+ve Leg</td>
<td>Pt–30% Rh (Tungsten–30% Rhodium)</td>
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<td>-ve Leg</td>
<td>Ni–Cr (Tungsten–5% Rhodium)</td>
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<tr>
<td>-ve Leg</td>
<td>W–26% Re</td>
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<td>-ve Leg</td>
<td>Cu–Ni</td>
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<td>-ve Leg</td>
<td>Ni–Al</td>
<td>-200 ~ 1300°C</td>
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<td>Pt–13% Rh</td>
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<td>-ve Leg</td>
<td>Ni–Cr–Si</td>
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</tr>
<tr>
<td>-ve Leg</td>
<td>Pt–10% Rh</td>
<td>-200 ~ 600°C</td>
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THERMOCOUPLE REFERENCE CHART

**TYPE**

- C
- E
- J
- K
- L
- N
- R
- S
- T
- U

**TEMPERATURE MEASUREMENT**

cygiddin@yahoo.com

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More information on Thermocouples….

<table>
<thead>
<tr>
<th>CODE</th>
<th>Approximate generated EMF change per degree Celsius change with reference junction at 0°C</th>
<th>Approximate working temperature range of measuring junction. NB not related to wire and conductor insulating material.</th>
<th>Conditions For Use</th>
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<td>68</td>
<td>81</td>
<td>–</td>
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<td>R</td>
<td>8</td>
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<tr>
<td>T</td>
<td>46</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Resistance Temperature

Resistance thermometry utilizes the characteristics relationship of electrical resistance with temperature to measure temperature, generally as follow;

\[ R_t = R_o (1 + \alpha t) \]

where,  
- \( R_t \) = resistance at temperature \( t \)
- \( R_o \) = resistance at reference temperature (usually at ice point, 0°C)
- \( \alpha \) = temperature coefficient of resistance

For pure metals, this relationship can be expressed as;

\[ R_t = R_o (1 + at + bt^2 + ct^3 + \ldots) \]

where,  
- \( R_t \) = resistance at temperature \( t \)
- \( R_o \) = resistance at reference temperature (usually at ice point, 0°C)
- \( a \) = temperature coefficient of resistance
- \( b, c \) = coefficient calculated on the basis of two or more known resistance-temperature (calibrated) points

Significant temperature measurement accuracy improvement can be attained using a temperature sensor that is matched to a temperature transmitter. This matching process entails teaching the temperature transmitter the relationship between resistance and temperature for a specific RTD sensor. This relationship, approximated by the Callendar-Van Dusen equation, is described as:

\[ R_t = R_o + R_o \alpha[t – \delta(0.01t – 1)(0.01t) – \beta(0.01t – 1)(0.01t^3)] \]

where,  
- \( R_t \) = Resistance (ohms) at Temperature \( t \) (°C)
- \( R_o \) = Sensor-specific Constant (Resistance at \( t = 0 \) °C)
- \( \alpha \) = Sensor-specific Constant
- \( \delta \) = Sensor-specific Constant
- \( \beta \) = Sensor-specific Constant (0 at \( t > 0 \) °C; 0.11 at \( t < 0 \) °C)

The exact values for \( R_o, \alpha, \delta, \beta \), known as Callendar-Van Dusen constants – are specific to each RTD sensor, and are established by testing each individual sensor at various temperatures. The Callendar-Van Dusen equation is but one method of describing the resistance versus temperature (R vs. T) relationship for platinum RTDs. International standard IEC 751 interprets the R vs. T relationship using an approach that is similar to the Callendar-Van Dusen methodology (see International Resistance vs. Temperature Chart (IEC 751)).

RTD requires a bridge circuit to give an indication analogous to temperature. The Wheatstone Bridge, as an instrument, is useful for measuring resistance very accurately and with the use of minimum amount of current flow through the circuits, as follow;

Adjustment of the three resistors is made so that zero current flows in the galvanometer. Note that if \( R_1 \) and \( R_2 \) are made equal, and \( R_x \) is adjusted to the same value as \( R_3 \), no current will flow through galvanometer because voltage drop will be exactly equal to both sides.

\[ \frac{R_1}{R_2} = \frac{R_x}{R_3} \]

hence, we can see that,  
\[ R_x = \frac{R_1 \cdot R_3}{R_2} \]
Industrial resistance thermometers, often referred to as **Resistance Temperature Detectors** (RTD), usually are made with elements of platinum (Pt), nickel (Ni), or copper (Cu). The entire resistance thermometer is an assembly of parts which includes the sensing element, internal lead wires, internal supporting and insulating materials and protection tube or case.

**Platinum RTD**

Platinum RTD is most commonly found used in industries, such as Pt100 or Pt200. This is because, of all material currently utilises in the fabrication of thermo resistive elements, platinum has the optimum characteristics for service over a wide temperature range. Although platinum is as a noble metal and does not oxidise, it is subject to contamination at elevated temperature by some gases, such as carbon monoxide and other reducing atmospheres, and by metallic oxides.

The metal is available commercially in pure form, providing a reproducible resistance-temperature characteristic. Platinum with a temperature coefficient of resistance equal to $0.00385 \, \Omega$ per °C (from 0 to 100 °C) has been used as standard for industrial thermometers.

Platinum has a high melting point and does not volatilise appreciably at temperature below 1200 °C. It has a tensile strength of 18,000 psi and a resistivity of $60 \, \Omega / (\text{cir mil}) (\text{ft})$ at 0 °C (9.83 $\Omega$ per cm).

Platinum is the material most generally used in the construction of precision laboratory standard thermometers for calibration work. In fact, the laboratory grade platinum resistance thermometer (usually with a basic resistance equal to 25.5 $\Omega$ at 0 °C) is the defining standard for the temperature range from the liquid oxygen point (-182.96 °C) to the antimony point (630.74 °C) as defined by the International Practical Temperature Scale of 1968 (IPTS 68).

The bulbs are generally limited to approximately 550 °C with occasional use up to 850 °C.
RTD Circuits

Two-Wire RTD Circuit
The simplest circuit uses a two-wire RTD. The RTD simply replaces one bridge element and causes the bridge to become unbalanced as its resistance changes. The output is read directly or used to drive other circuitry in the transmitter. If the RTD is located at any distance from the transmitter (and bridge), then lead wires of a more economical material are used to connect the RTD to the bridge. One drawback of the two-wire approach is that the lead wires add resistance to the circuit and can cause error in the reading.

Three-Wire RTD Circuit
To help eliminate the error introduced by lead wire effects, a three-wire RTD is commonly used. In this approach, the resistance effects of each of the lead wires (A and B in the figure to the right) are canceled by the bridge because each is in an opposite leg of the bridge. The third lead (C) is a sensing lead. The three-wire approach does not eliminate all lead wire effects. But because sensors are generally located fairly close to their transmitters, lead wire effects are small and the approach provides reasonable accuracy.

Four-Wire RTD Circuit
The most effective way to eliminate lead wire effects is with any of several versions of the four-wire approach. An approach that does not require a bridge is shown to the right. In this method, a constant current power source is connected to two of the RTD leads. The voltage drop across the RTD is measured at the other two leads. The voltage drop is independent of lead wire effects.
SUMMARY EQUATIONS OF RTD CIRCUITS

**Two-Lead measuring circuit**

\[
R_1 + R_3 = R_2 + a + b + X \\
R_1 = R_2 \\
R_3 = a + b + X
\]

**Three-Lead measuring circuit**

\[
R_1 + R_3 + a + c = R_2 + b + c + X \\
R_1 = R_2 \\
\text{If } a = b \text{ (lead resistance equal)} \\
\text{Then, } R_3 = X
\]

**Four-Lead measuring circuit**

\[
R_1 + Ra + C + C = R_2 + T + X + C \\
\text{but } R_1 = R_2 \\
Ra + C = T + X \quad \text{--------- (1)}
\]

\[
R_1 + R_b + T + t = R_2 + C + X + t \\
\text{but } R_1 = R_2 \\
R_b + C = T + X \quad \text{--------- (2)}
\]

Summing equations (1) and (2), yields:

\[
R_a + R_b + C + T = T + C + 2X \\
X = \frac{R_a + R_b}{2}
\]
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<th>°C</th>
<th>Ohm</th>
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<td>264.81</td>
<td>670</td>
<td>335.39</td>
</tr>
</tbody>
</table>

**NOTE**

To convert from °C to °F:

\[ 1.8 \times (°C) + 32 = °F \]

Example: (1.8 \times 100) + 32 = 212 °F

To convert from °F to °C:

\[ 0.556 (°F) – 32 = °C \]

Example: 0.556 (212 – 32) = 100 °C
Radiation Types (Pyrometer)

When temperature must be measured and physical contact with the medium to be measured is impossible or impractical, use is made of thermal radiation or optical pyrometry methods and equipment.

Radiation pyrometry measures the radiant heat emitted or reflected by a hot object. Practical radiation pyrometers are sensitive to a limited wavelength band of radiant energy, although theory indicates that they should be sensitive to the entire spectrum of energy radiated by the object. The operation of thermal radiation pyrometers is based on blackbody concepts and has made possible the measurement and automatic control of temperature under conditions not feasible with other temperature sensing elements.

Theory of Radiation Measurements

A perfect radiating body, traditionally called a blackbody, is used as the comparative standard to measure quantitatively the energy radiated by a hot object.

The thermal radiation energy and temperature relationship for a blackbody condition can be expressed as:

\[ W = kT_0^4 \]

where,  
\( W \) = Radiant energy emitted per unit area from the blackbody.  
\( k \) = Stefan-Boltzmann constant.  
\( T_0 \) = absolute temperature in Kelvin.

This is the Stefan-Boltzmann law and assumes the blackbody to be radiating to a receiver which is at absolute zero.

In practical applications for thermal radiation pyrometers, the transfer of radiant thermal energy takes place at temperatures above absolute zero. Thus equation has to be modified to express the radiant energy and temperature relationship under these conditions. The new equation can be expressed as:

\[ W = \sigma (T^4 - T_0^4) \]

Where,  
\( \sigma \) = a constant.  
\( T \) = absolute temperature of the blackbody.  
\( T_0 \) = absolute temperature of the surroundings.

Emissivity

In general a rough black surface radiates more heat than a smooth bright surface at the same temperature. This effect is called emissivity and is expressed in numbers from 1 to 0. A blackbody or perfect radiator of thermal energy has an emissivity of 1. Less perfect radiating bodies have an emissivity of less than 1.

Some very thin transparent surfaces have emissivities very close to zero. Other surfaces such as plastics, rubber, and textiles have emissivities close to 1. Metals have varying emissivities depending on their surface and composition. Emissivity is important, because many types of thermal radiation pyrometers require a correction to compensate for emissivity effects.
**Thermal Radiation Pyrometry**

Thermal radiation pyrometers essentially operate according to the Stefan, Boltzmann law. This means that the pyrometer must be designed to have a wavelength response for the desired temperature range. The essential parts of a basic radiation pyrometer are shown in *figure 17*. The lens or mirrors used must be capable of passing or reflecting the wavelengths of the radiant energy emitted by the hot object, and focusing them on the receiving detector which gives either an emf output or undergoes a resistance change. This output can then be measured in terms of temperature by the measuring device.

![Figure 17: Schematic of a basic radiation pyrometer](image)

**Radiation Pyrometer Applications**

Radiation pyrometers are used industrially where temperatures are above the practical operating range of thermocouples, where thermocouple life is short because of corrosive atmospheres, where the object whose temperature is to be measured is moving, inside vacuum or pressure furnaces, where temperature sensors would damage the product (such as growing crystals), and for obtaining the temperature of a large surface when it is impractical to attach primary temperature sensors.
**Optical Pyrometers**

Optical pyrometers are not suitable for recording or controlling temperatures but they provide an accurate method of measuring temperature between 600 °C and 3000 °C, and are very useful for checking and calibrating total radiation pyrometers.

They may be divided into two groups. In the first group, the light of a given wavelength from the hot body is optically matched with the light from a constant comparison lamp in the instrument by means of an optical wedge or polarising system.

In the second group, which has now become by far the most popular, the brightness of the light from the calibrated comparison lamp is varied to match the brightness of the light from the hot body. The brightness of the lamp is judged to be the same as that of the source when it merges into the image of the source. The instrument is, therefore, known as the *Disappearing*.

![Figure 19: Schematic of an optical pyrometer in which the brightness of the source image is varied by an optical wedge.](image-url)