AE 242
Aerospace Measurements Laboratory

Temperature Measurement

Length, mass, time and temperature are fundamental units and others are derived from these. Temperature is different compared to other fundamental quantities. It cannot be divided, multiplied like other quantities. Two bodies of like length are combined and total length is twice. When two bodies at same temperature are joined, temperature remains same. Final temperature is defined by thermal equilibrium. Temperature measurement is always a measurement of some other physical quantity which is dependent on it.

Temperature Measurement

Temperature dependent physical properties:

1. Changes in physical dimensions

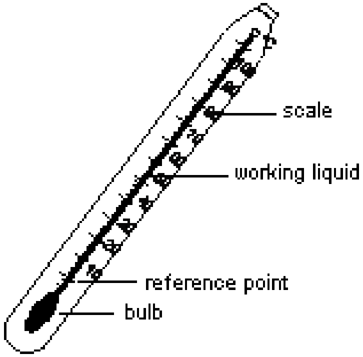
    a) Liquid-in-glass thermometers b) Bimetallic elements

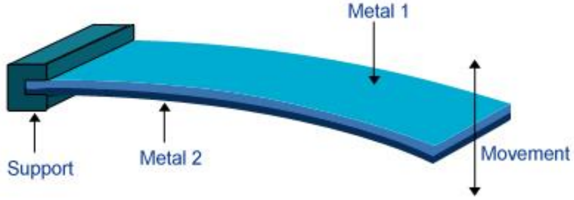
2. Changes in gas pressure or vapor pressure

    a) Constant volume gas thermometers b) Pressure thermometers (gas, vapor and liquid filled)

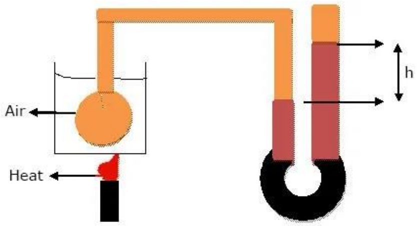
3. Changes in Electrical properties

    a) Resistance thermometers (RTD), b) Thermistors, c) Thermocouples





Bi-Metalic Strip



Constant volume gas thermometer

Temperature Measurement

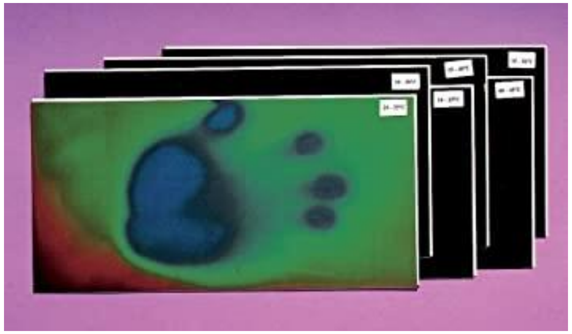
Temperature dependent physical properties:

4 Changes in emitted thermal radiation

a) Thermal and photon sensors b) Total radiation-pyrometer c) Optical and two color pyrometer d) Infrared pyrometers

5 Changes in chemical phase

a) Fusible indicators b) Liquid crystals c) Temperature-reference cells



Temperature scales

Common temperature scales are Fahrenheit and Celsius. These are based on number of increments between freezing point and boiling point of water. Celsius is 100 units and Fahrenheit is 180 units.

$$\mathbf{F} = 32 + \frac{9}{5}\mathbf{C}^{\mathbf{o}}$$

Absolute temperature is in Kelvin scale $K = 273.15 + C^{o}$

Rankine scale is $$\mathbf{R} = \frac{9}{5}\mathbf{K}$$

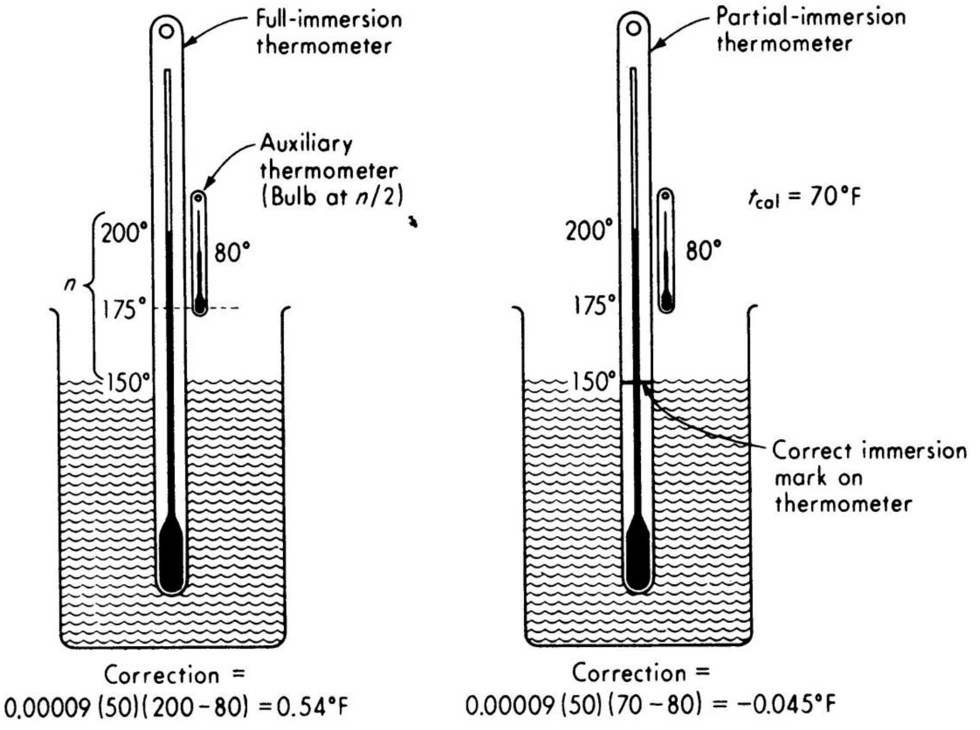
Zero point on Kelvin scale and Rankine scale represents the same physical state. Related by constant ratio.

Liquid-in Glass thermometer

Consist of a large bulb at the lower end, capillary tube with scale, and a liquid filling bulb and capillary. Change in temperature changes the volume of liquid due to thermal expansion. Coefficient of thermal expansion of liquid is very high compared to glass. For higher temperature range, pressure above the liquid is high to control boiling point. Two types:

Total immersion type: Calibrated for when liquid column is fully immersed.

Partial immersion : Calibrated for immersion up to a definite mark and the exposed portion at a definite temperature.



Liquid-in Glass thermometer

Some of the desired features:

1) Linear instrument scale

2) Large coefficient of thermal expansion of liquid

3) Liquid should not change phase in the temperature range. Mercury is limited by freezing point –38.87 C^o and alcohol by boiling point.

4) Liquid should be clearly visible when drawn into fine thread

5) Liquid should not adhere to wall, any film remaining on wall will reduce the volume.

Thermoelectric effects

Thermoelectricity phenomena: Temperature difference creates electrical potential or electric potential creates temperature difference.

Three such phenomenon are: 1) Seebeck Effect 2) Peltier Effect 3) Thomson effect

Thermoelectric effects

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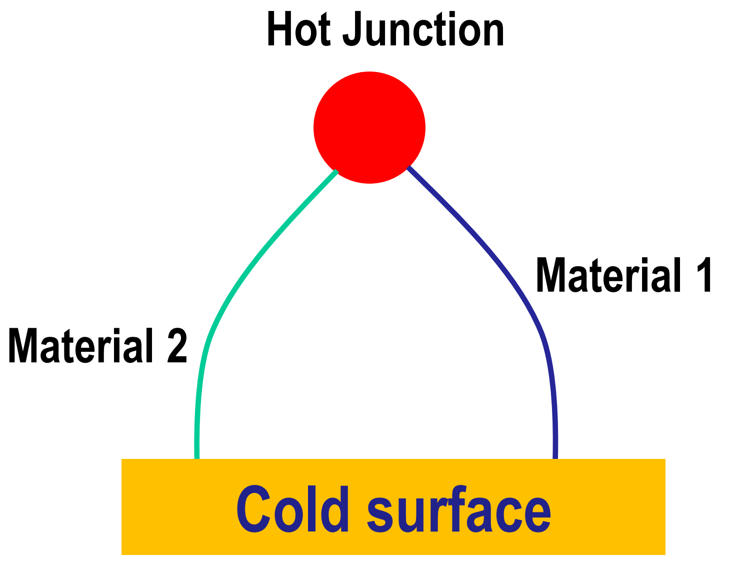
Seebeck Effect: When a junction of two different material is subjected to temperature difference, electrical potential is produced in the circuit. Temperature difference generates voltage.



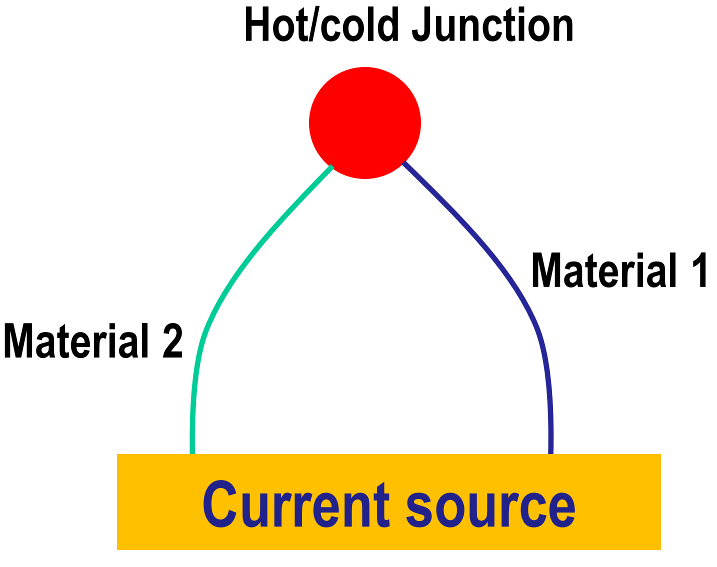
$$S = -\frac{\Delta V}{\Delta T}$$

Thermoelectric effects

Thermoelectricity phenomena: Temperature difference creates electrical potential or electric potential creates temperature difference.

Three such phenomenon are: 1) Seebeck Effect 2) Peltier Effect 3) Thomson effect

Peltier Effect: When current passes through a junction of two different materials, heat may be generated or absorbed depending on the current direction.



$$\Pi = \frac{q}{I}$$

Thermoelectric effects

Thermoelectricity phenomena: Temperature difference creates electrical potential or electric potential creates temperature difference.

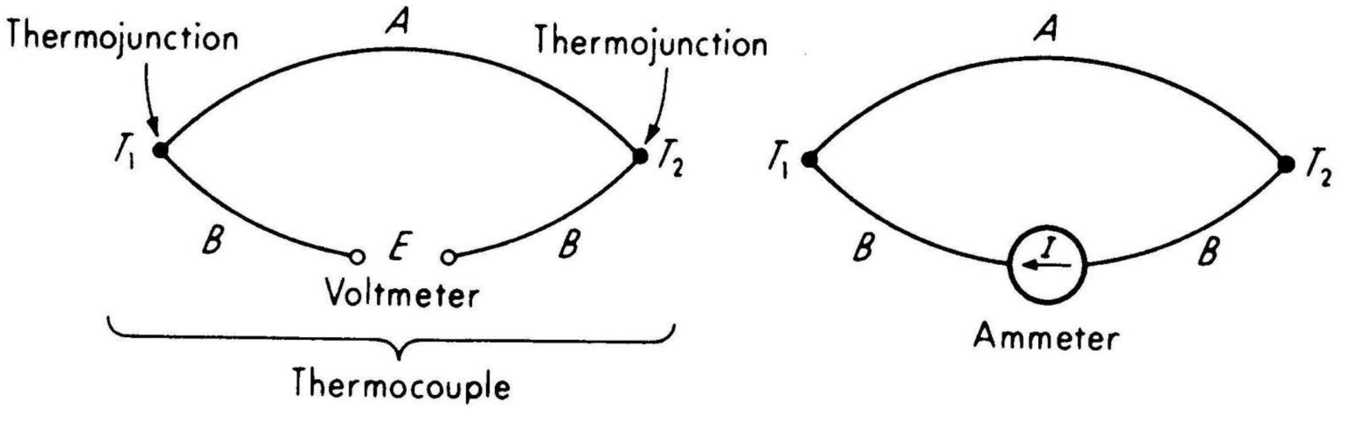
Three such phenomenon are: 1) Seebeck Effect 2) Peltier Effect 3) Thomson effect

Thomson Effect: Heat is absorbed or released in a conductor when the current flow through a conductor having temperature gradient.

$$\tau = \frac{1}{I}\,\frac{dq}{dx}\Big/\frac{dT}{dx}$$

Thermocouple

Two wires of different materials A & B are connected with one junction at temperature T_1 and other at T_2, voltmeter detects emf E and an ammeter detects current I. E and I depends on the material and temperatures T_1 and T_2. This is called Seebeck effect. The process is reversible i.e. if current flows through the junction it will cool or heat. Thermocouple offers simple construction. Twisted wires of different material can work as thermocouple. It is direct conversion of thermal energy to electrical energy.

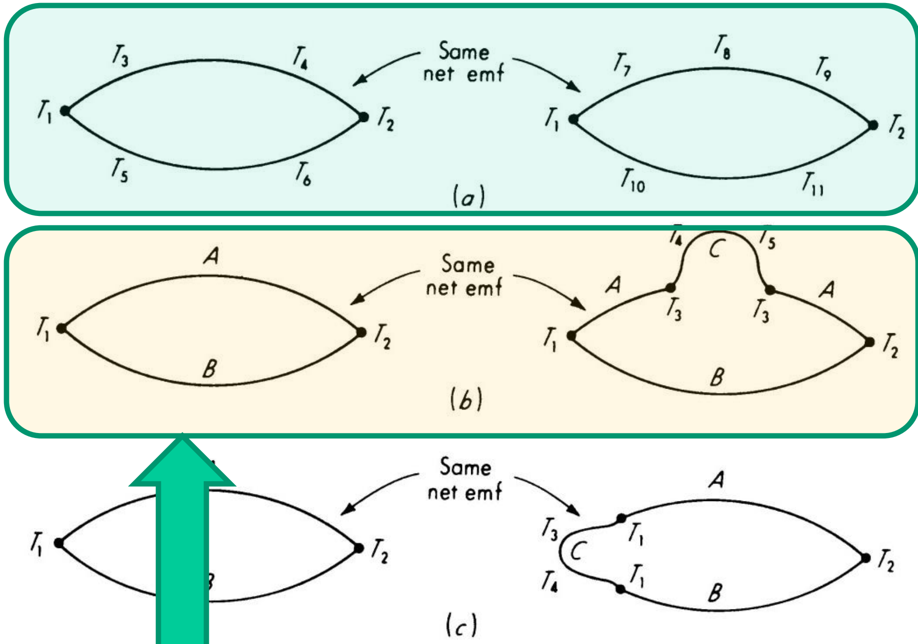


Thermocouple

Laws of thermocouple behavior:

a) The thermal emf of a thermocouple with junctions at T_1 and T_2 is totally unaffected by temperature elsewhere in the circuit if the two metals used are each homogeneous.

Lead wires can be exposed to an unknown/varying temperature environment without effecting the voltage produced.



b) If a third homogeneous metal C is inserted into either A or B, as long as the two thermo-junctions are at like temperatures, the net emf of the circuit is unchanged irrespective of the temperature of C away from the junctions.

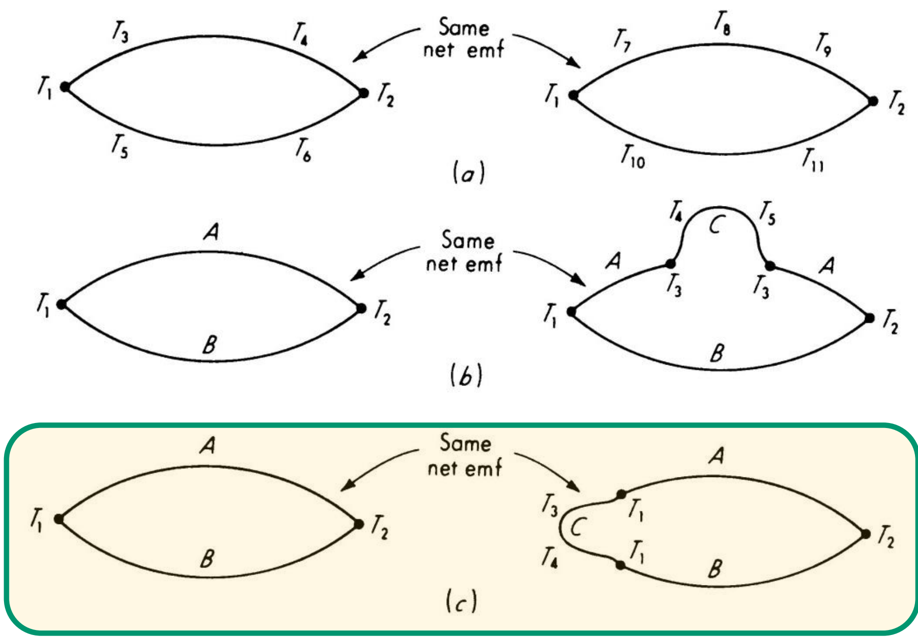
Any other emf measuring device can be inserted without altering the output.

Thermocouple

Laws of thermocouple behavior:

c) If metal C is inserted between A and B at one of the junctions, the temperature of C at any point away from AC and BC junctions is immaterial. As long as the junctions AC and BC are both at the temperature T_1, the net emf is the same as if C was not there.

Thermocouple junctions can be soldered or brazed without effecting the output



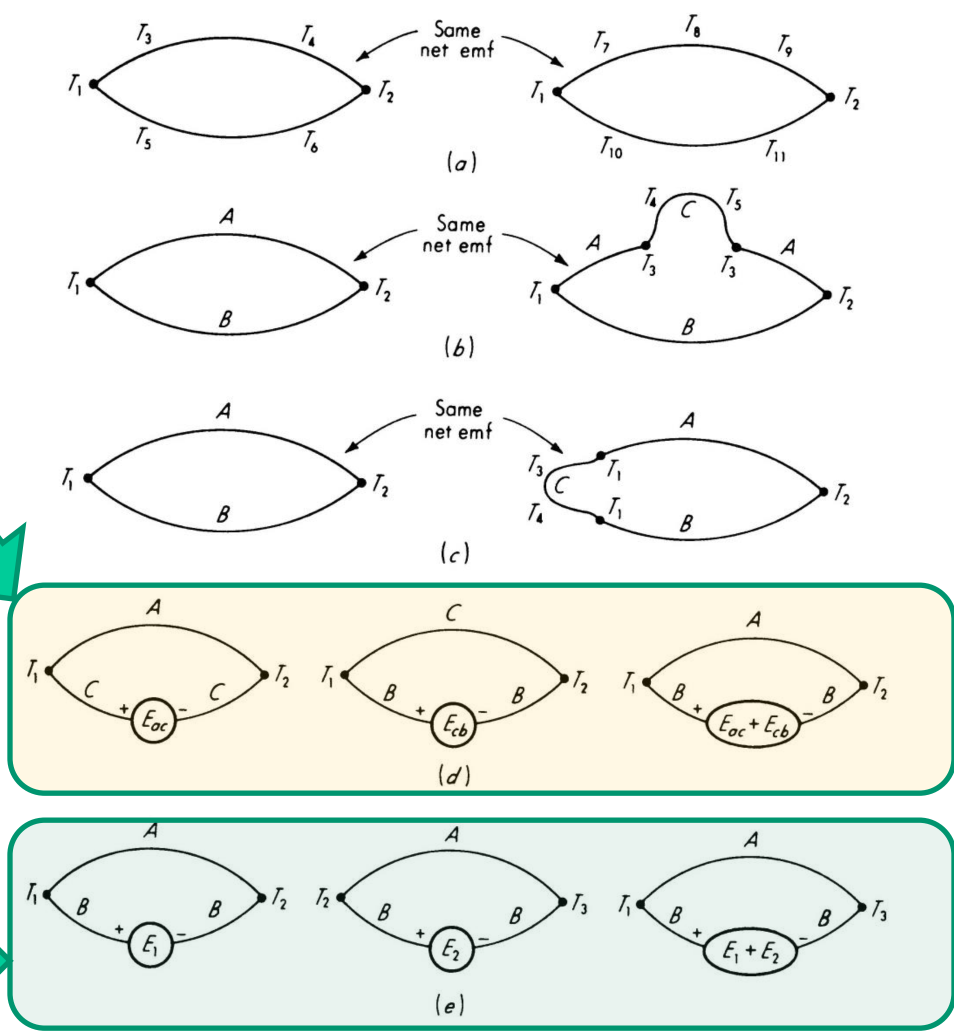
Thermocouple

Laws of thermocouple behavior:

d) If the thermal emf of metals A and C is E_{AC} and that of metals B an C is E_{CB}, then the thermal emf of metals A and B is $E_{AC} + E_{CB}$

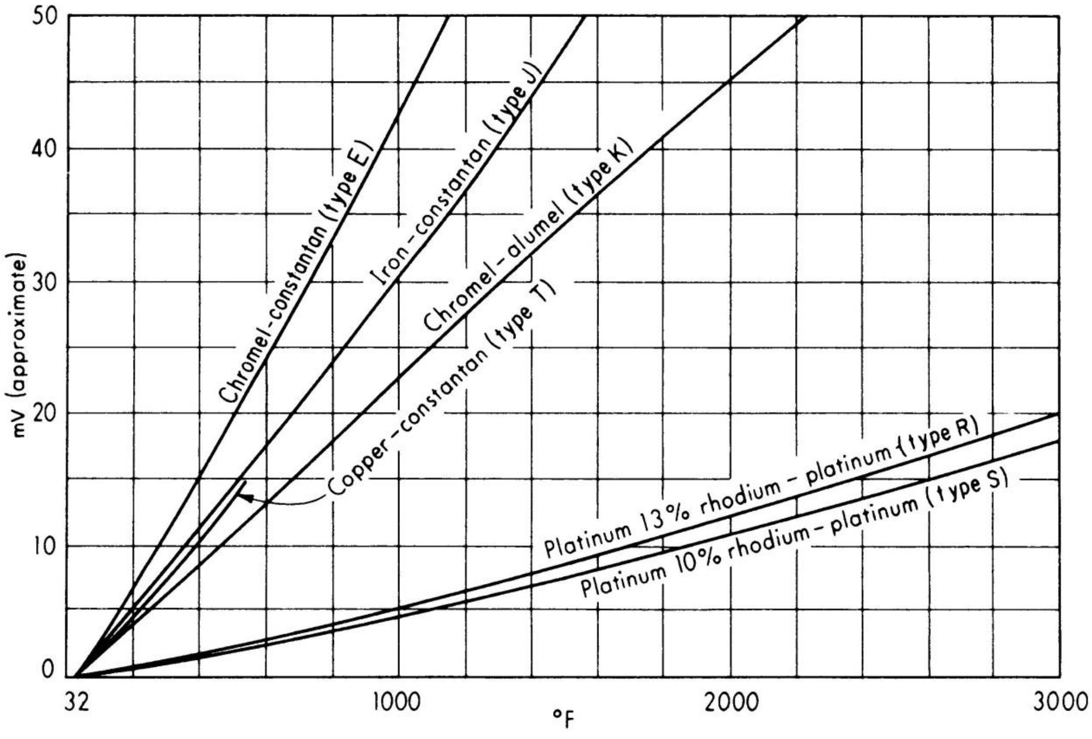
All possible pairs of metals need not be calibrated

e) If a thermocouple produces emf E_1 when its junctions are at T_1 and T_2, and E_2 when at T_2 and T_3, then it produces E_1+E_2 when the junctions are at T_1 and T_3. Temperature of one of the junction should be known to find out the unknown temperature.

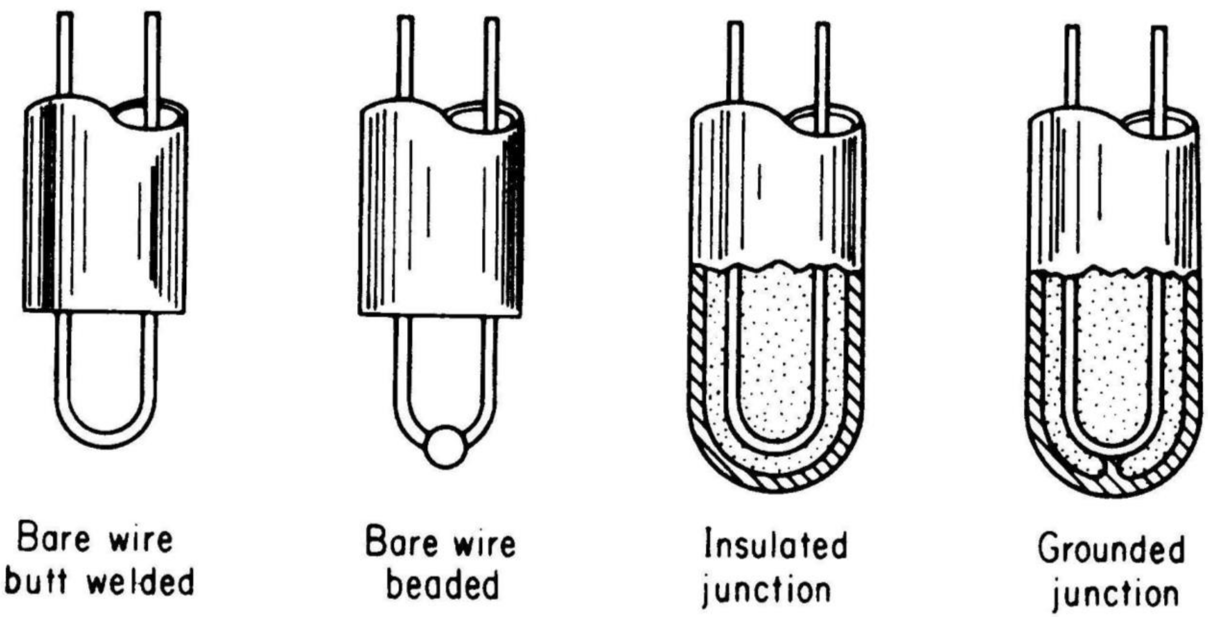


Common thermocouples

Chromel/Alumel couples are useful over the range of –200 to 1200 C^o. Platinum/Platinum-rhodium 0 to 1500 C^o, Chemically inert at high temperatures in oxidizing conditions. Copper/Constantan is used from –200 C^o to 350 C^o. Copper oxidizes above 350 C^o. Iron/Constantan is widely used in industry and it can be used from –150 to 1000 C^o



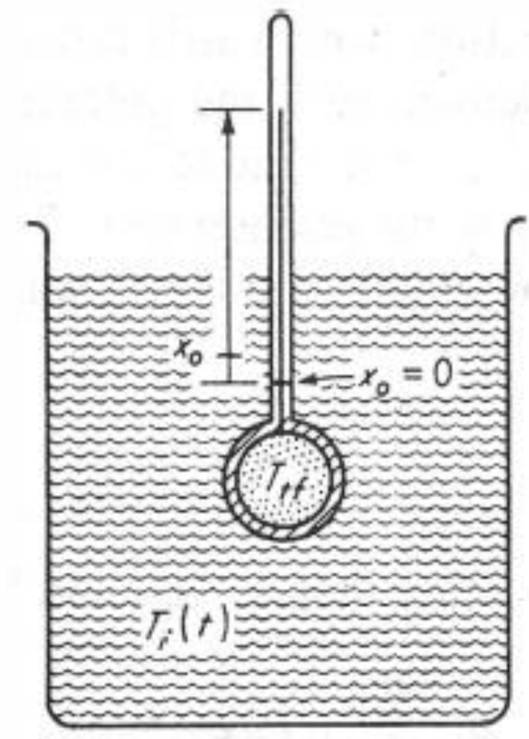
Thermocouple construction



Liquid-in-glass thermometer

Linear scale is calibrated for temperature around the bulb. When surrounding temperature is changing with time, output will also change. Motion of the liquid in capillary is governed by

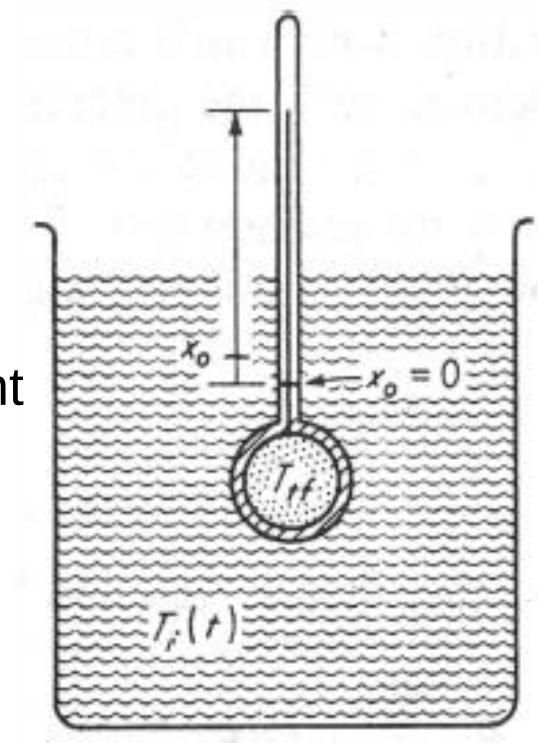
1) Coefficient of thermal expansion of capillary liquid
2) Coefficient of thermal expansion of thermometer body
3) Coefficient of heat transfer between thermometer external wall and medium around it
4) Specific heat of capillary liquid
5) Density of the capillary liquid
6) Volume of the capillary liquid
7) Surface tension of capillary liquid and wall
8) Thermal conductivity of the thermometer wall



Liquid-in-glass thermometer

Following assumptions are made

1) Bulb wall and film around bulb wall are pure thermal resistance, do not store any thermal energy
2) Heat transfer area remains constant
3) Overall film coefficient remains constant
4) No heat is lost from the thermometer
5) Mass of the fluid in the bulb is constant
6) Specific heat of the capillary tube remains constant



Liquid-in-glass thermometer

Scale output can be related to temperature and other thermometer quantities

Volume change = linear displacement x area $\boxed{= x_0 A_c}$

Volume change = Coefficient of thermal expansion x volume x temperature change $\boxed{= K_{ex} V_b T_{tf}}$

$$\boxed{x_0 = \frac{K_{ex} V_b}{A_c} T_{tf}}$$

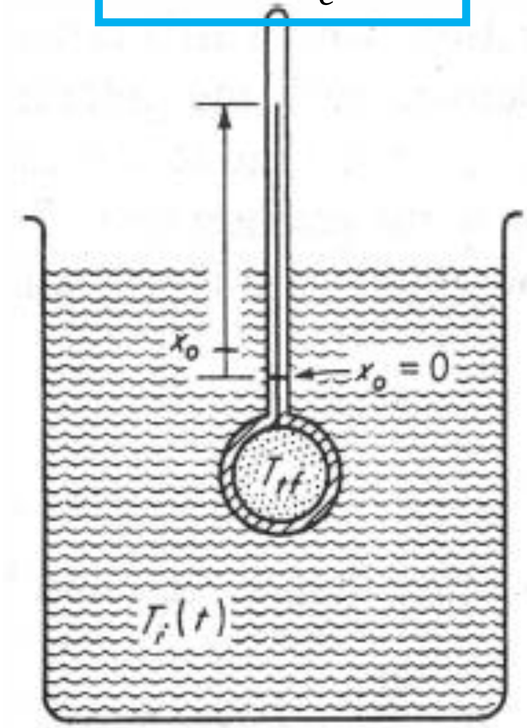
$x_0 =$ dispalcement from reference mark m

$K_{ex} =$ differential expansion coefficeint of thermometer fluid and bulb glass, $m^3/(m^3\ {}^0C)$

$T_{tf} =$ temperature of fluid in bulb (assumed uniform throughout bulb volume), $T_{tf} = 0$ when $x_0 = 0,\ {}^0C$

$V_b =$ volume of bulb, m^3

$A_c =$ cross-sectional area of capliallry tube, m^2



Liquid-in-glass thermometer

Balancing the heat energy i.e. heat energy from surrounding medium to capillary liquid

Convection heat transfer = heat transfer coefficient x area x temperature difference

Energy stored = specific heat x mass x temperature difference

Heat in - heat out = energy stored

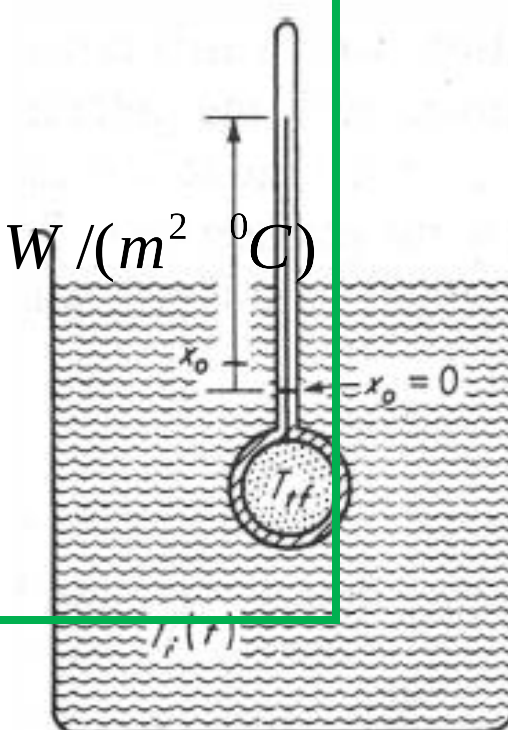
$$UA_b(T_i - T_{tf})dt - 0(\text{assume no heat loss}) = V_b \rho C dT_{tf}$$

U = overall heat transfer coefficient across bulb wall, $W/(m^2\ {}^0C)$

A_b = heat transfer area of bulb wall, m^2

ρ = mass desnity of thermometer fluid, kg/m^3

C = specific heat of thermometer fluid, $J/(kg\ {}^0C)$



Liquid-in-glass thermometer

$$x_0 = \frac{K_{ex} V_b}{A_c} T_{tf}$$

$$T_{tf} = x_0 \frac{A_c}{K_{ex} V_b}$$

$$\frac{dT_{tf}}{dt} = \frac{dx_0}{dt} \frac{A_c}{K_{ex} V_b}$$

$$UA_b(T_i - T_{tf})dt - 0(\text{assume no heat loss}) = V_b \rho C dT_{tf}$$

$$V_b \rho C \frac{dT_{tf}}{dt} + UA_b T_{tf} = UA_b T_i$$

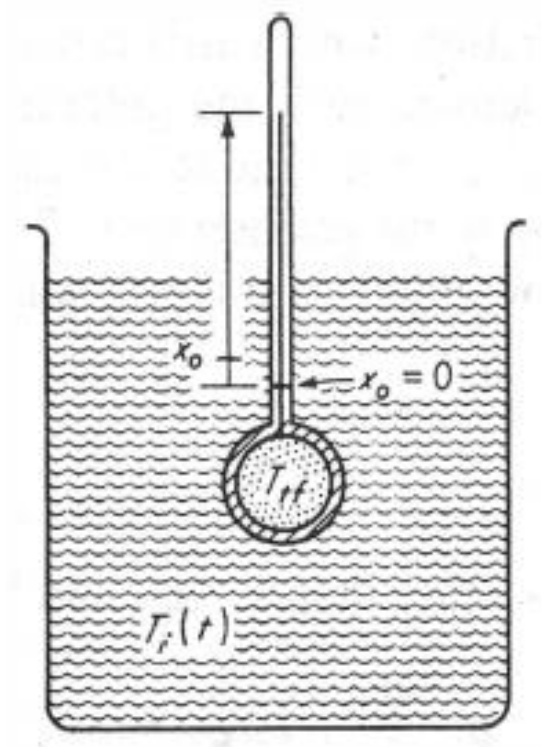
$$\frac{A_c \rho C}{K_{ex}} \frac{dx_0}{dt} + \frac{UA_b A_c}{K_{ex} V_b} x_0 = UA_b T_i$$

$$\frac{\rho C V_b}{UA_b} \frac{dx_0}{dt} + x_0 = \frac{K_{ex} V_b}{A_c} T_i$$

$$K = \frac{K_{ex} V_b}{A_c} \quad m/{}^0C$$

$$\tau = \frac{\rho C V_b}{UA_b} \quad s$$

$$\boxed{\tau \frac{dx_0}{dt} + x_0 = KT_i}$$



Electrical-Resistance sensors

Electrical resistance changes with temperature and it is reproducible. Two types:

1) Conductors (Metals) 2) Semiconductors

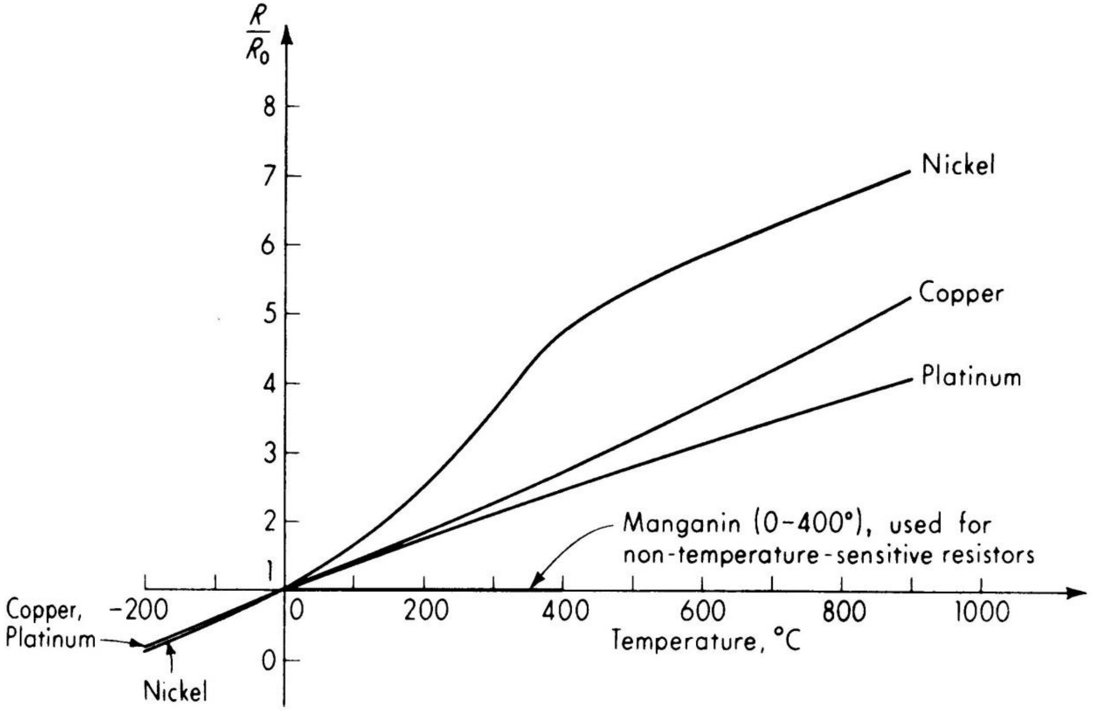
Conducting material based are called resistance thermometer, sometimes Resistance Temperature Detector (RTD). Resistance increases with increase in temperature. Semiconductor based sensors are called thermistor. Resistance decreases with increase in temperature. Any technique for measuring resistance change can be used for temperature measurement.

Conductive sensors-Resistance thermometers

Variation of resistance R with temperature for most metallic materials

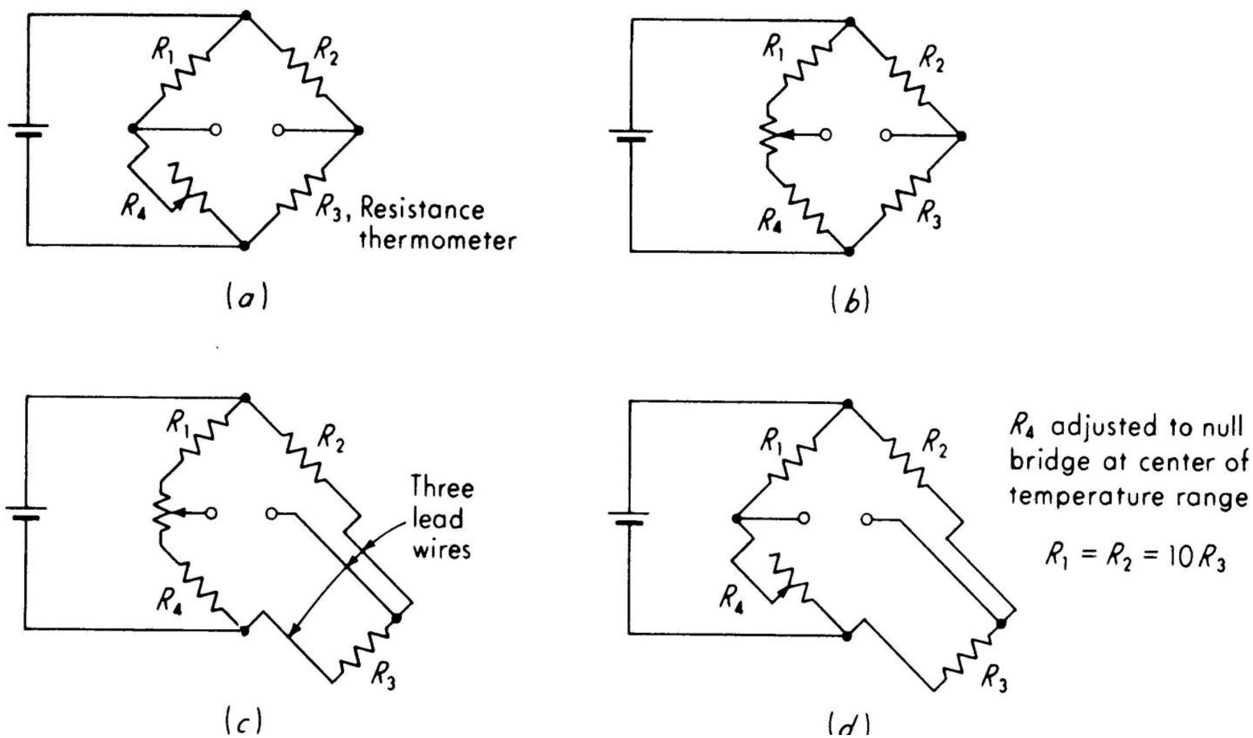
$$\mathbf{R} = \mathbf{R}_0(1 + \mathbf{a}_1\mathbf{T} + \mathbf{a}_2\mathbf{T}^2 + \ldots + \mathbf{a}_n\mathbf{T}^n)$$

R_0 is resistance at temperature T = 0 (^{o}C) and a_1, a_2. ..a_n are constants. Number of terms depends on the material and accuracy. Platinum, Nickel and copper are commonly used material.



Conductive sensors-Resistance thermometers

Bridge circuit could be deflection mode or null mode. In null mode on of the resistor is varied until balance is obtained. When higher accuracy is required arrangement (b) is used. For lead wire temperature compensation three wire arrangement is used. Self heating of the RTD is a issue in such arrangement. R1=R2=10R3 reduces non-linearity in the output.



Bulk semiconductor sensors

Semiconductor sensors have large negative temperature coefficients. These are highly non-linear. Resistance/temperature relationship:

$$R = R_0 e^{\beta(1/T - 1/T_0)}$$

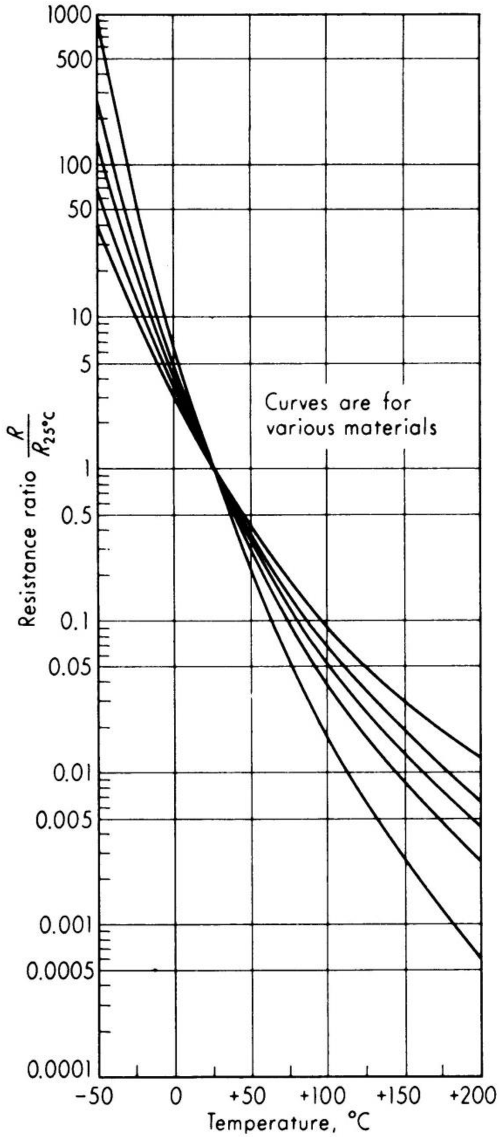
R = resistance at temperature T, Ω

R_0 = resistance at temperature T_0, Ω

β = constant, characteristic of material K

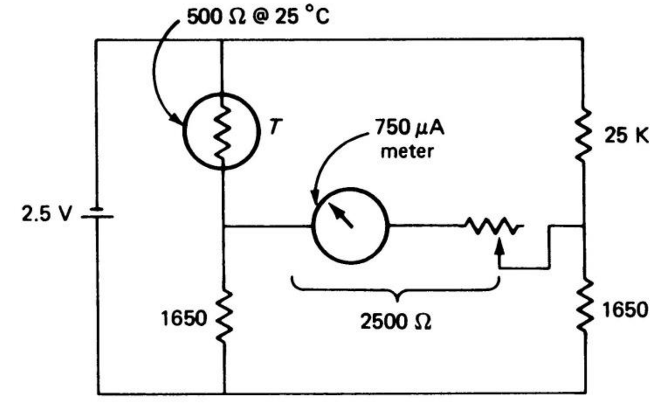
T, T_0 = absolute temperature, K

Temperature co-efficient for semiconductor gage is –0.045 and for platinum it is +0.0036

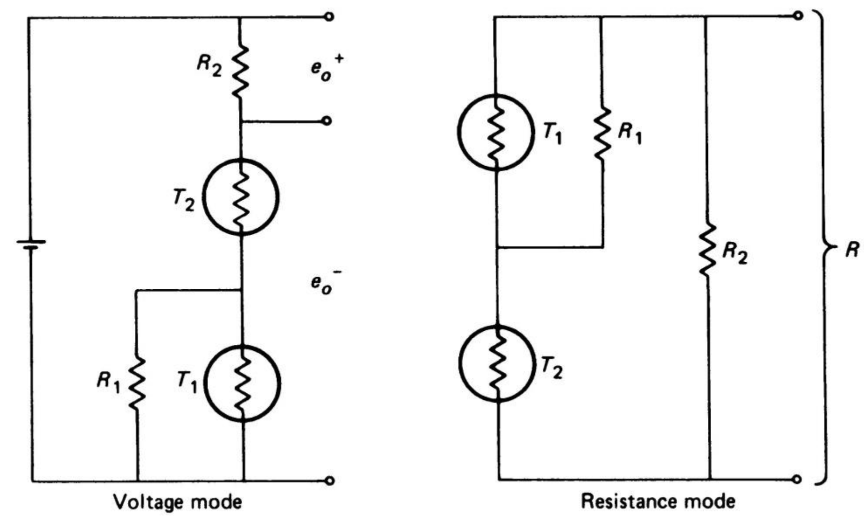


Bulk semiconductor sensors

Readymade semiconductor sensors are available which can be used directly as voltage mode or resistance mode. These are available as linear output when temperature is changed. This is achieved by the resistance network.



(a)



(b)

Radiation methods

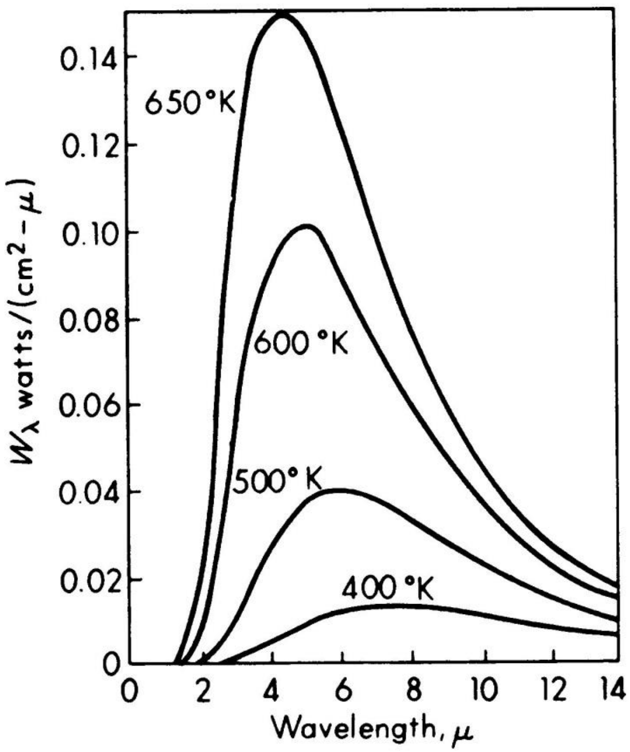
It is a non contact type method. This method is applicable for very high temperature measurement. Measurement device is not at temperature to be measured. Very convenient for moving bodies. Can be used for scanning surface temperature. Applications are: missile guidance – infrared emissions from hot jet exhaust and homes on it, space craft attitude – able to distinguish the radiation from moon, earth and other planets. Radiation method can be used for stress measurements in cyclically loaded material.

This is also called as pyrometry, in Greek “pyros” means fire and “metron” means to measure.

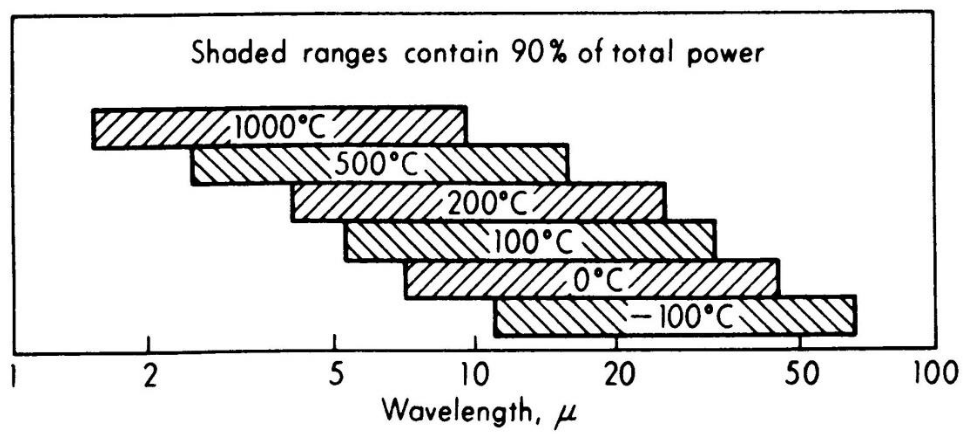
Theoretically radiation pyrometers can be used at any distance from the temperature source. Dust, smoke, some gasses absorb the radiation and intensity reduces in practical case.

Radiation methods

For a given temperature waves of all the wavelengths are emitted. The intensity of a particular wavelength is dependent on temperature. Larger peaks are obtained for high temperature.



(a)



(b)

Radiation pyrometer

Complete radiation sensing instruments. Blackened thermopile is used as a detector, radiation energy is focused by mirrors or lens.

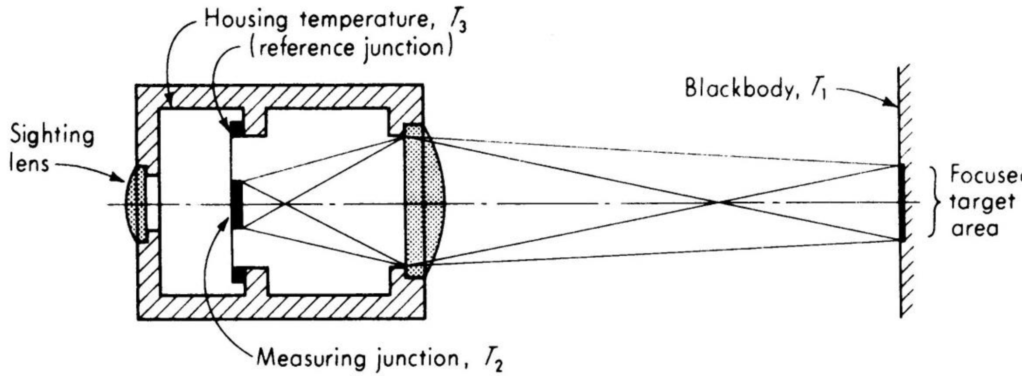
Very simple analysis

Heat loss = radiant heat input

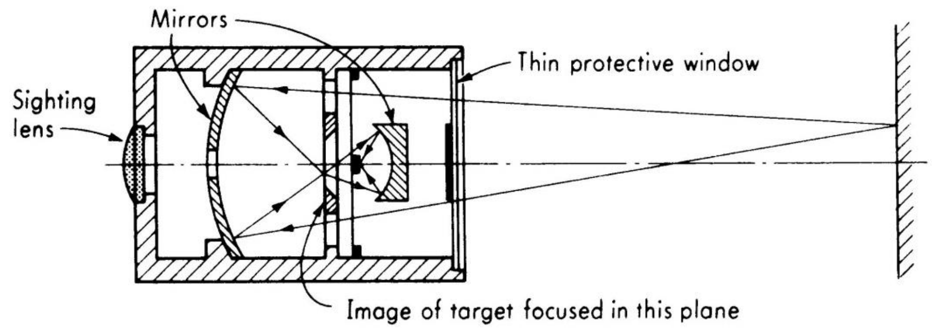
$$\mathbf{K}_1(\mathbf{T}_2 - \mathbf{T}_3) = \mathbf{K}_2\mathbf{T}_1^4$$

Thermocouple voltage output is proportional to $(T_2 - T_3)$ and it is proportional to T_1^4

Thermopiles can be as large as 30. Depends on the response required. Less number will have fast response but less sensitivity.



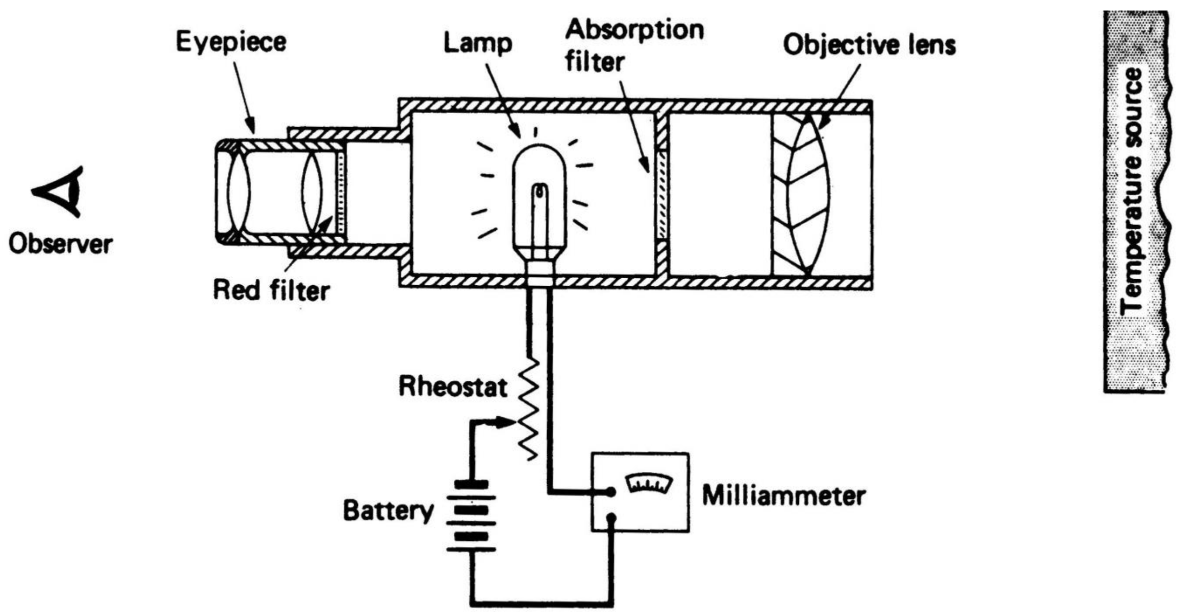
Lens-type radiation thermometer



Mirror-type radiation thermometer

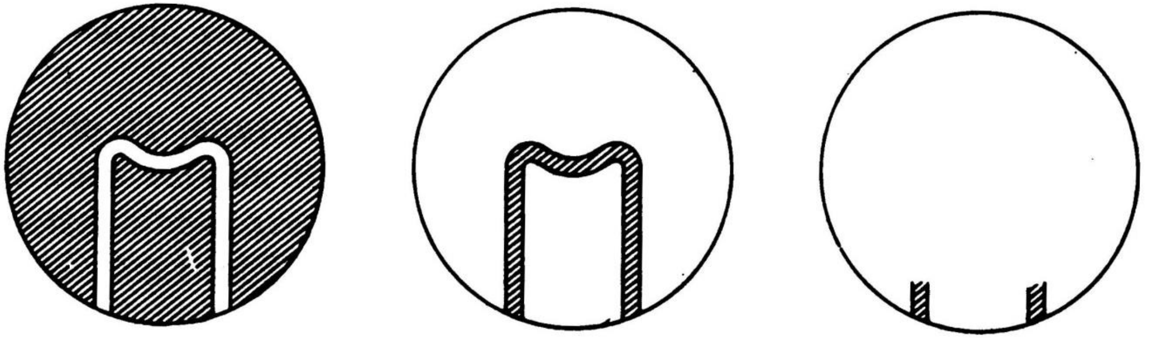
Disappearing filament pyrometer

Intensity of an electrically heated filament is matched with the source intensity at a particular wavelength. Objective lens focuses the source in the plane of the lamp filament. Source appears to be superimposed on the filament to the observer. Absorption filter is used to reduce the intensity of radiation and it increases the life of filament. Color filter is used to obtain monochromatic conditions.



Disappearing filament pyrometer

Filament intensity can be changed by changing current in it. It can be made disappear with proper adjustment of current. Current is mapped to temperature measurement.



(a) Filament too hot (b) Filament too cold (c) Filament and source at same temperature

Thermal expansion method - bimetallic

Thermal expansion is different for different material. Two strips A & B with different thermal coefficient of expansions α_A and α_B at the same temperatures and bonded firmly together.

$$\rho = \frac{\mathbf{t}\{3(1+\mathbf{m}^2)+(1+\mathbf{mn})[\mathbf{m}^2+1/(\mathbf{mn})]\}}{6(\alpha_A-\alpha_B)(\mathbf{T}_2-\mathbf{T}_1)(1+\mathbf{m}^2)}$$

ρ= radius of curvature

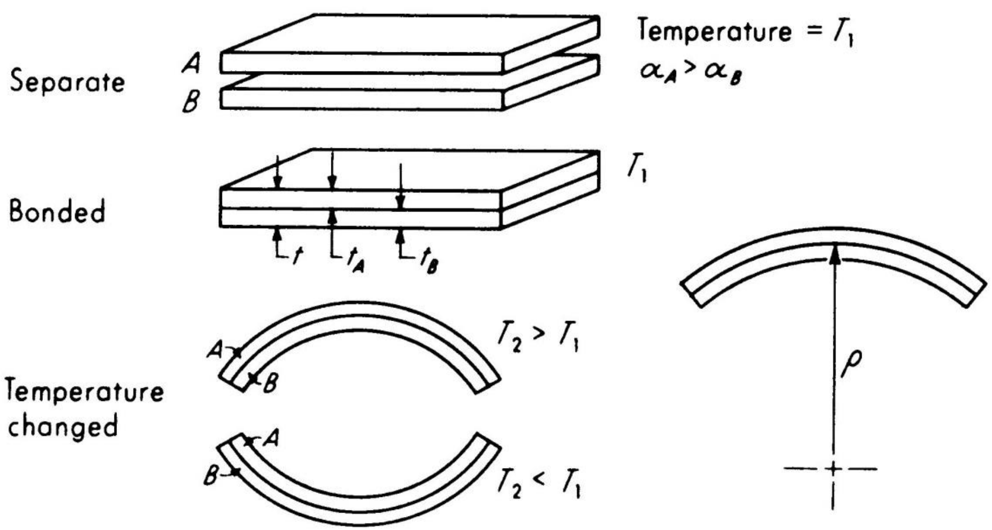
t = total strip thickness

n = Elastic modulus ratio E_B/E_A

m = Thickness ratio t_B/t_A

T_2-T_1 = Temperature rise

$t_B/t_A \cong 1$ and $n+1/n \cong 2$



$$\rho = \frac{2\mathbf{t}}{3(\alpha_A-\alpha_B)(\mathbf{T}_2-\mathbf{T}_1)}$$

Thermal expansion method - bimetallic

Practical usable material has positive thermal coefficient of expansion. One layer is made out of Invar, nickel alloy having almost zero coefficient of thermal expansion [1.7 10^{-6} in/in ^{o}C]. The mechanical movement of the material can be recorded by suitable interface or directly to control. Common application is temperature dependent switches.