UNIT - V:

THERMAL SENSORS

PSG College of
Technology, Coimbatore

SENSORS FOR ENGINEERING APPLICATIONS

23I202

Content of the Course – Sensors for Engineering applications 231202

STRAIN AND PRESSURE MEASUREMENT	ELECTRONIC SENSORS	MOTION SENSORS	LIGHT SENSORS	THERMAL SENSORS
Resistance strain gauge Piezoelectric pressure sensor, characteristics Electronic circuits for strain gauge load cells Interferometer Capacitance pressure sensor	Inductive, Capacitive and ultrasonic based proximity sensors Reed switch Hall-effect switching sensors Capacitive based humidity sensor Liquid level detectors, Flow sensors Smoke sensors	Capacitor plate sensor Inductive sensors LVDT Accelerometer systems Rotation sensors Piezoelectric devices for motion sensing Hall effect-based speed sensor.	Color temperature Light flux Photo sensors, Photo resistor and photoconductors, Photodiodes, Phototransistors, Photovoltaic devices, Fiber-optic sensors (FOS): Fibre-optic pressure sensor and its applications LIDAR	Bimetallic strip, Semiconductor based Temperature sensor, Thermocouples, Resistance thermometers, Thermistors, PTC and NTC thermistors Semiconductor-based applications. Infrared sensors: bolometer, Pyroelectric detector, semiconductor based IR sensors.

CONTENTS

UNIT - V

- Bimetallic strip
- Semiconductor based Temperature sensor
- Thermocouple
- Resistance thermometers
- Thermistors, PTC and NTC thermistors
- Infrared sensors: bolometer
- Pyroelectric detector, semiconductor based IR sensors.

CONTENTS

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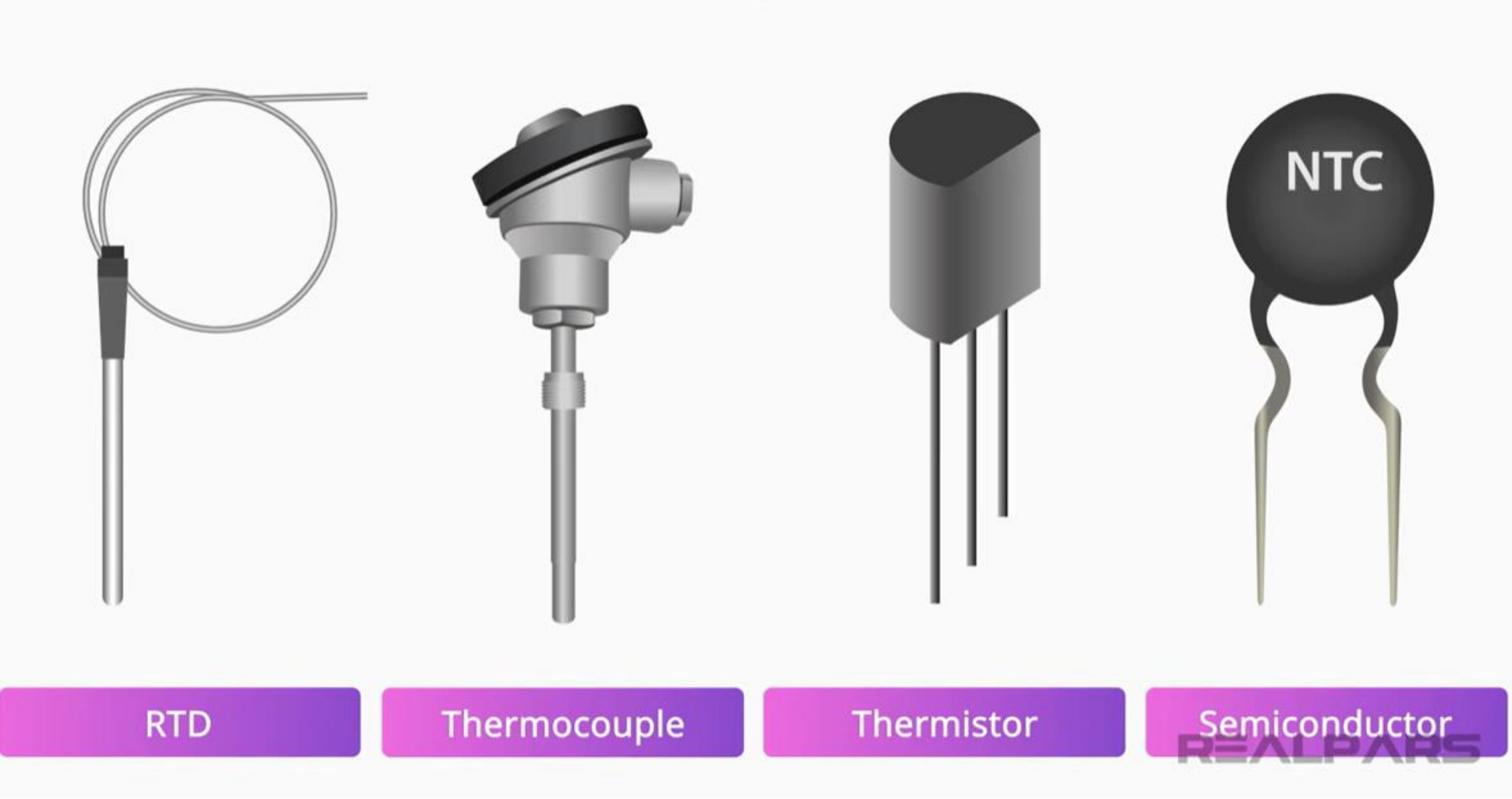
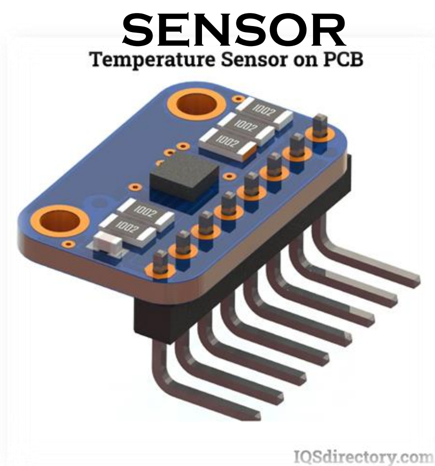
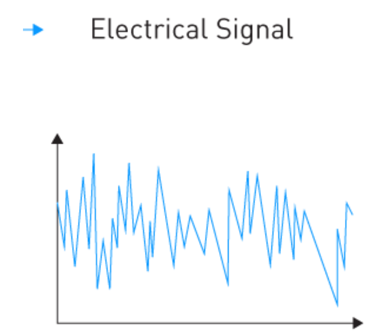


Thermal Sensors

Thermal sensors are devices designed to detect, measure, and convert thermal energy (heat) into an electrical signal or visual representation.





Input
Temperature/heat

→

THERMAL SENSOR
(or Detector)

→

Output
(Electrical Signal)
Visual output

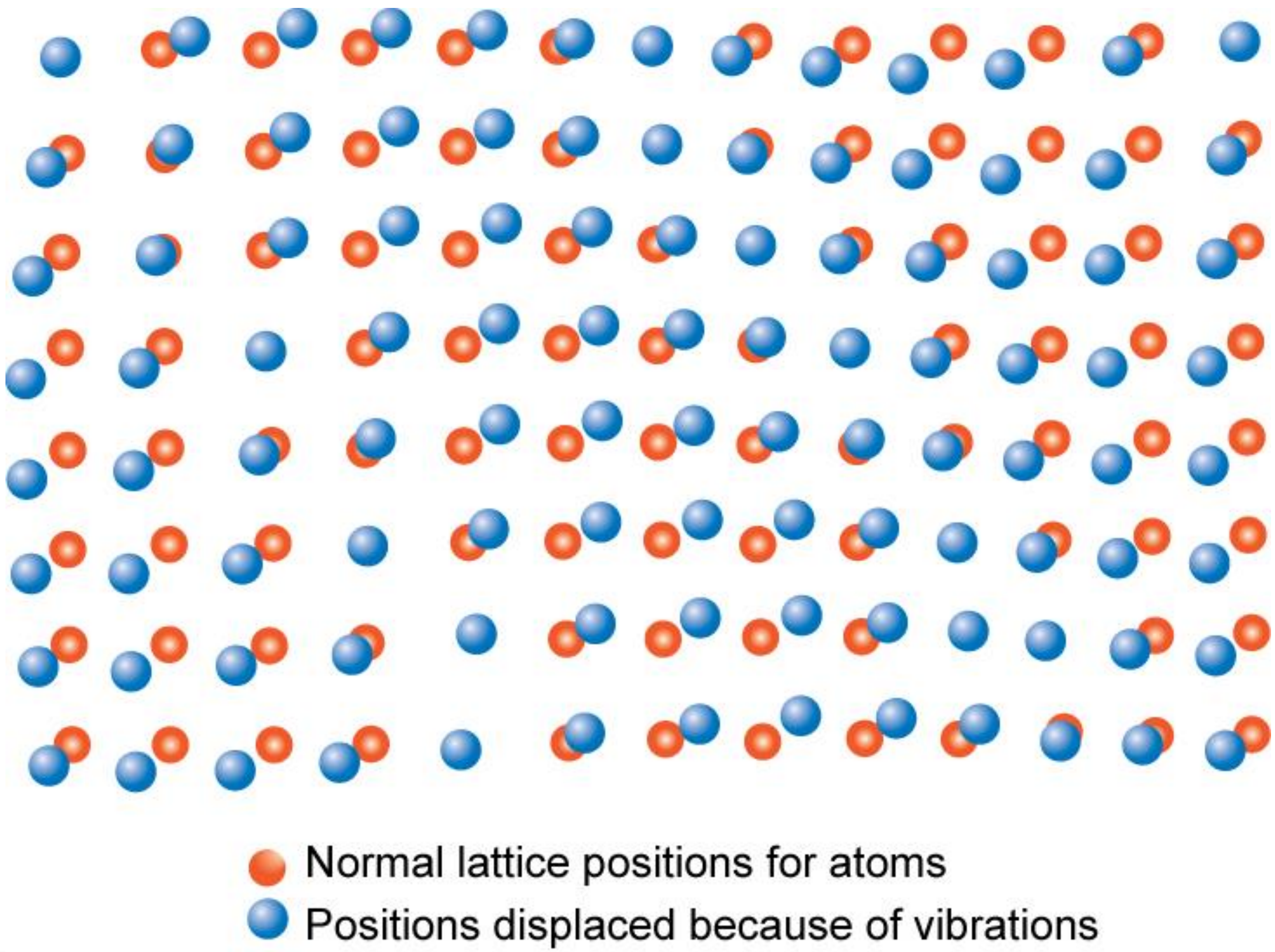
Thermal Properties of Materials

The following are the various thermal characteristics of Material:

1. **Temperature**
2. **Specific Heat**
3. **Heat capacity**
4. **Thermal conductivity**
5. **Melting point**
6. **Thermal diffusivity**
7. **Thermal shock resistance**

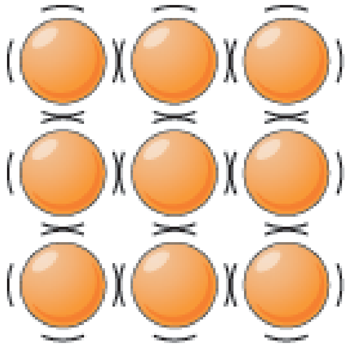
Atomic Vibrations

Atomic vibrations are in the form of lattice waves or **phonons**

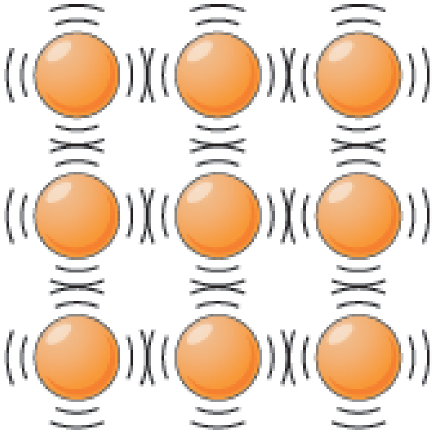


Thermal Expansion

Liquids expand more when heated than solids.



Cold



Hot

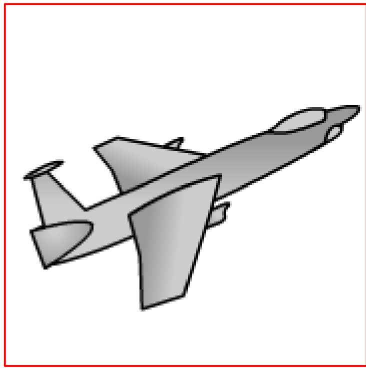
Gases expand more when heated than liquids (depending upon P, V and T)

When heated, solids (and liquids and gases) gain thermal energy. The particles start to move about more – their vibrations take up more space, so there is expansion in all directions. The opposite is true when the temperature falls – the material will get smaller (contract).

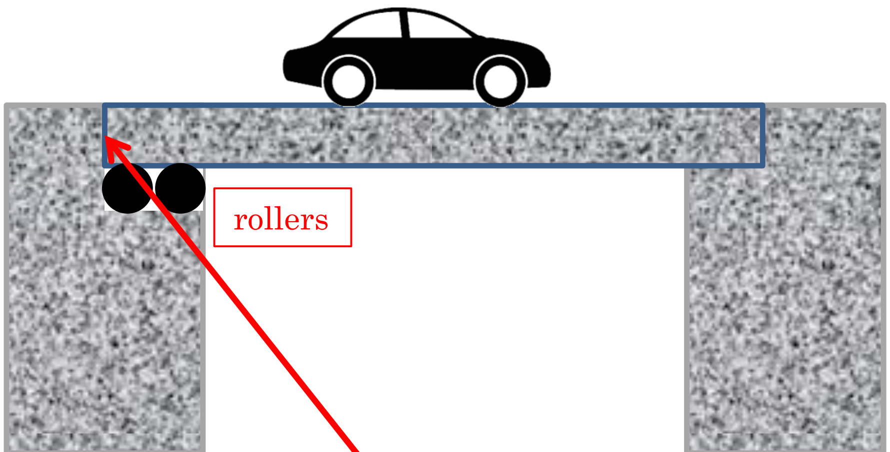
Material	Coefficient of expansion
Glass	8.5
Concrete	12
Brass	19
Steel	11
Aluminium	23

Thermal Expansion - examples

- Girders in buildings and bridges are made with gaps at the ends.
- Glass to be used in cooking has to be a low expansion type such as Pyrex otherwise it would shatter as it got hot.
- Rivets are heated before they are put in place to hold two metal plates together.

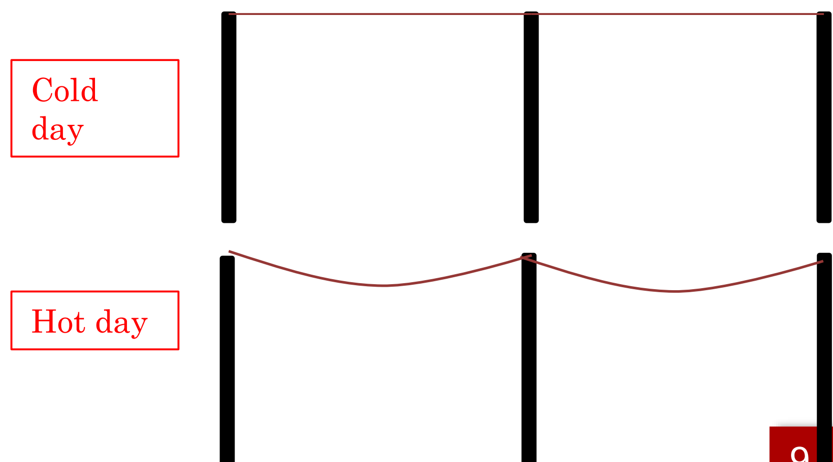


High-speed planes are warmed by air friction and so get longer.



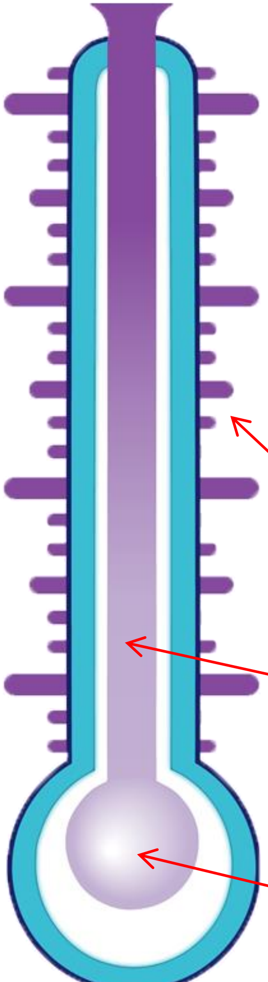
Bridges have gaps to allow for expansion. Rollers may be used at one end so that movement can take place.

Suspended overhead cables are left slack to allow for contraction that could happen on a very cold day.



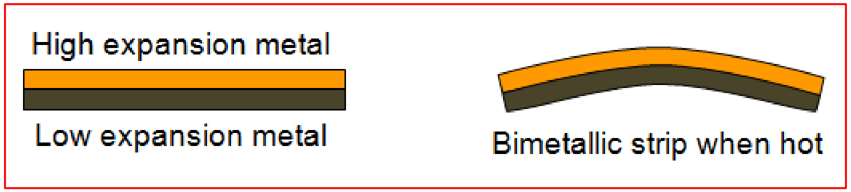
Thermal Expansion - applications

Thermometer

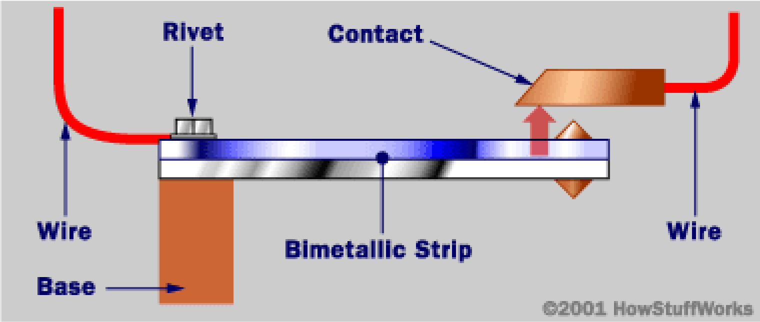


As the temperature rises, the liquid in the bulb expands, and so rises up the narrow tube which is calibrated to fixed points (eg. 0°C, 100°C)

Bimetallic strip



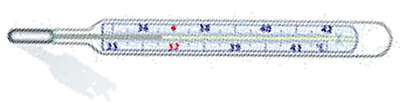
In a bimetallic strip, a low expansion metal (eg. Invar) is bonded to a high expansion metal (eg. Brass). As the strip is heated, the brass expands more than the invar, causing the strip to bend.



Bimetallic strips may be used in thermostats – devices for maintaining a steady temperature, such as in water heaters.

Measuring temperature

- Examples of thermometers



digital thermometer

<u>Clinical thermometer</u>.
- Measures human temperatures very accurately. Scale is restricted to a few degrees either side of the normal body temperature (37°C). A restriction in the neck stops the mercury from dropping until the reading is taken.

<u>Digital Clinical thermometer</u>.
- Contains a thermistor inside the probe. As the temperature rises the thermistor becomes a much better conductor, causing a higher current to flow, and so a higher reading on the meter.

Heat Capacity

The ability of a material to absorb heat

- Quantitatively: The energy required to produce a unit rise in temperature for one mole of a material.

heat capacity (J/mol-K)

$$C = \frac{dQ}{dT}$$

energy input (J/mol)

temperature change (K)

- Two ways to measure heat capacity:

  C_p : Heat capacity at constant pressure.

  C_v : Heat capacity at constant volume.

  C_p usually > C_v

- Heat capacity has units of $\frac{\text{J}}{\text{mol} \cdot \text{K}} \left(\frac{\text{Btu}}{\text{lb} - \text{mol} \cdot {}^\circ\text{F}} \right)$

Specific Heat: Comparison

increasing c_p

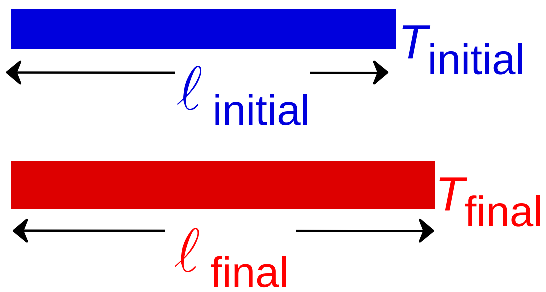
Material	c_p (J/kg-K) at room T
Polymers	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
Ceramics	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
Metals	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

c_p (specific heat): (J/kg-K)
C_p (heat capacity): (J/mol-K)

- Why is c_p significantly larger for polymers?

Thermal Expansion

Materials change size when temperature is changed



$T_{final} > T_{initial}$

$$\frac{l_{final} - l_{initial}}{l_{initial}} = \alpha_l (T_{final} - T_{initial})$$

linear coefficient of thermal expansion (1/K or 1/ºC)

Thermal Expansion: Example

Ex: A copper wire 15 m long is cooled from 40 to -9ºC. How much change in length will it experience?

- Answer: For Cu $\alpha_\ell = 16.5 \text{ x } 10^{-6} \; (^\circ\text{C})^{-1}$

rearranging Equation 19.3b

$$\Delta\ell = \alpha_\ell \ell_0 \Delta T = [16.5 \text{ x } 10^{-6}(1/^\circ\text{C})](15 \text{ m})[40^\circ\text{C} - (-9^\circ\text{C})]$$

$$\boxed{\Delta\ell = 0.012 \text{ m} = 12 \text{ mm}}$$

Thermal Conductivity

The ability of a material to transport heat.

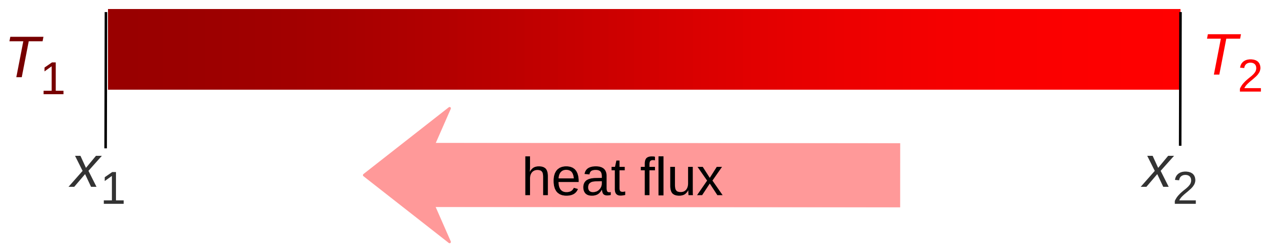
Fourier's Law

$$q = -k\frac{dT}{dx}$$

heat flux (J/m^2-s) — q

temperature gradient — $\frac{dT}{dx}$

thermal conductivity (J/m-K-s) — k



$T_2 > T_1$

- Atomic perspective: Atomic vibrations and free electrons in hotter regions transport energy to cooler regions.

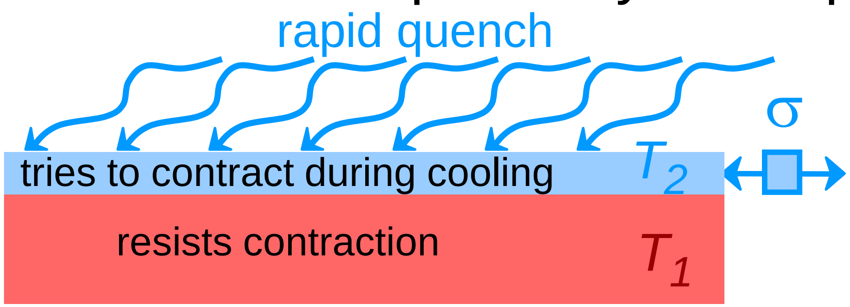
Thermal Conductivity: Comparison

increasing k

Material	k (W/m-K)	Energy Transfer Mechanism
• <u>Metals</u>		
Aluminum	247	atomic vibrations and motion of free electrons
Steel	52	
Tungsten	178	
Gold	315	
• <u>Ceramics</u>		
Magnesia (MgO)	38	atomic vibrations
Alumina (Al_2O_3)	39	
Soda-lime glass	1.7	
Silica (cryst. SiO_2)	1.4	
• <u>Polymers</u>		
Polypropylene	0.12	vibration/rotation of chain molecules
Polyethylene	0.46-0.50	
Polystyrene	0.13	
Teflon	0.25	

Thermal Shock Resistance

- Occurs due to: nonuniform heating/cooling
- Ex: Assume top thin layer is rapidly cooled from T_1 to T_2



Tension develops at surface

$$\sigma = -E\alpha_\ell (T_1 - T_2)$$

Temperature difference that can be produced by cooling:

$$(T_1 - T_2) = \frac{\text{quench rate}}{k}$$

Critical temperature difference for fracture (set $\sigma = \sigma_f$)

$$(T_1 - T_2)_{\text{fracture}} = \frac{\sigma_f}{E\alpha_\ell}$$

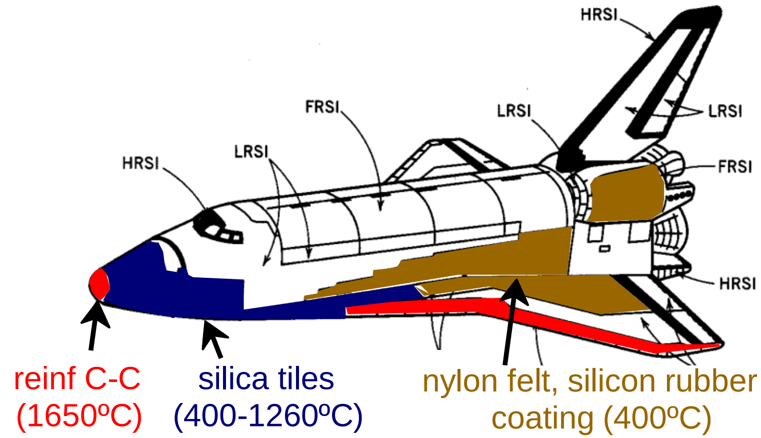
set equal

- $(\text{quench rate})_{\text{for fracture}} = \text{Thermal Shock Resistance } (\mathit{TSR}) \propto \dfrac{\sigma_f k}{E\alpha_\ell}$
- Large *TSR* when $\dfrac{\sigma_f k}{E\alpha_\ell}$ is large

Thermal Protection System

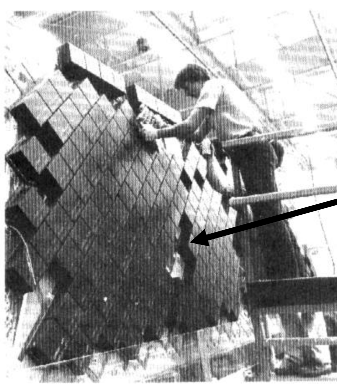
- Application:

Space Shuttle Orbiter

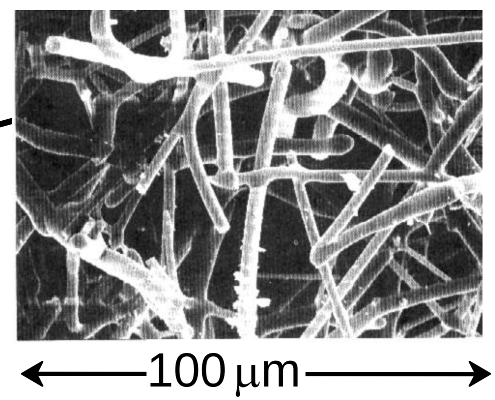


, "The Shuttle Orbiter Thermal Protection System", *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1189.)

- Silica tiles (400-1260ºC):
  -- large scale application



-- microstructure:



~90% porosity!
Si fibers bonded to one another during heat treatment.

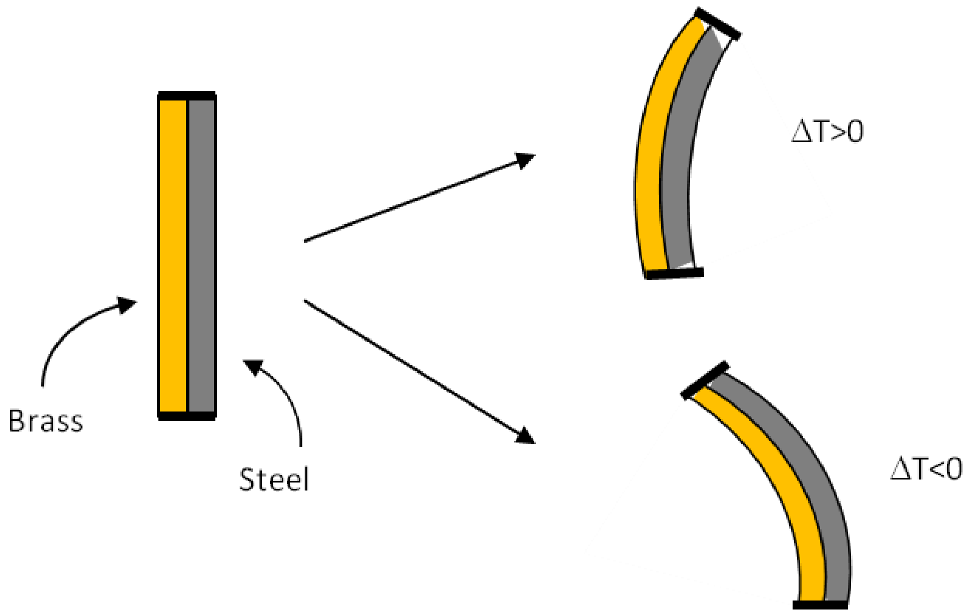
Fig. 19.3W, *Callister 5e*. (Fig. 19.3W courtesy the National Aeronautics and Space Administration.)

Summary

The thermal properties of materials include:

- **Heat capacity**:
  -- energy required to increase a mole of material by a unit *T*
  -- energy is stored as atomic vibrations
- **Coefficient of thermal expansion**:
  -- the size of a material changes with a change in temperature
  -- polymers have the largest values
- **Thermal conductivity**:
  -- the ability of a material to transport heat
  -- metals have the largest values
- **Thermal shock resistance**:
  -- the ability of a material to be rapidly cooled and not fracture
  -- is proportional to $\frac{\sigma_f k}{E\alpha_\ell}$

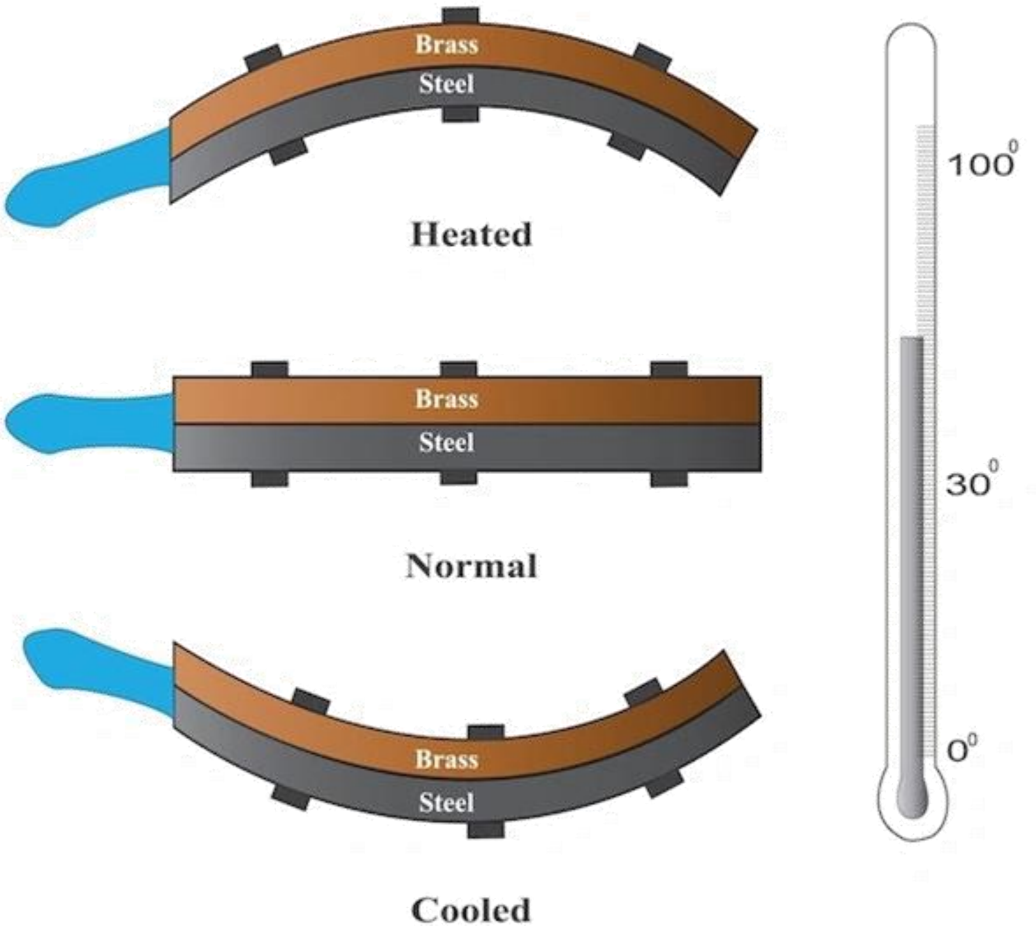
Bi Metallic Strip



A **bimetallic strip** is composed of two dissimilar metals joined together, usually in the form of two strips or two ribbons.

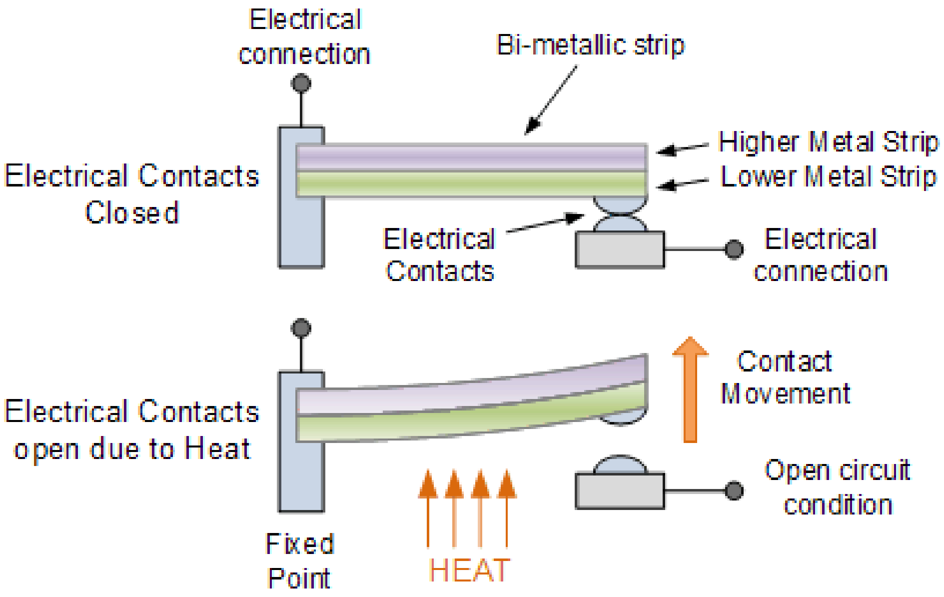
The two metals are specifically dissimilar in terms of their electrical conductivity, thermal conductivity, and mechanical properties.

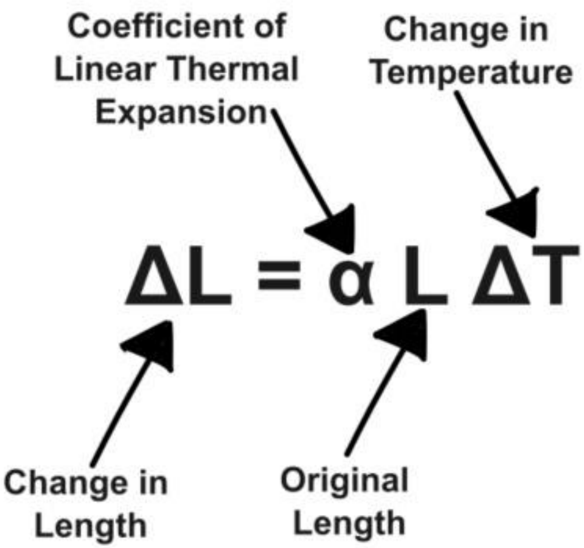
Bi Metallic Strip

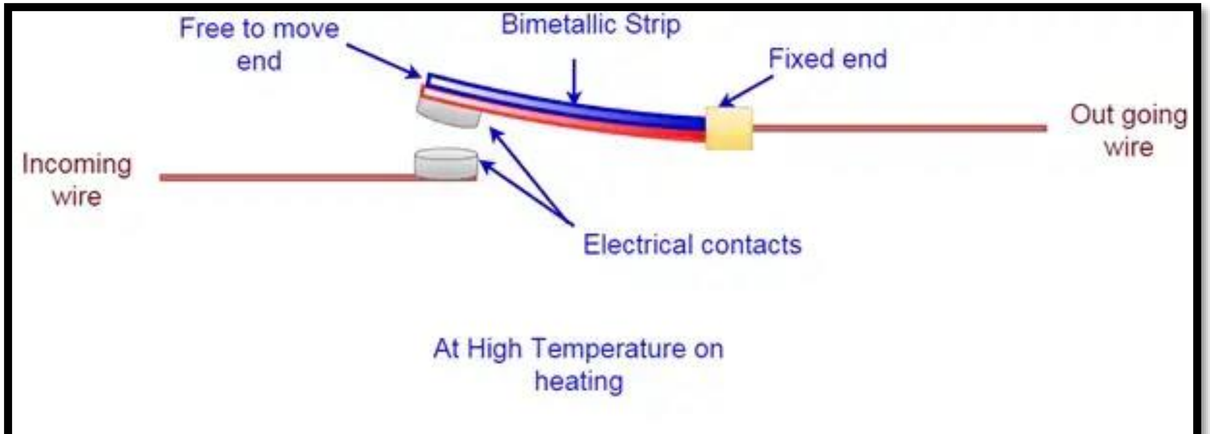


- When the strip is exposed to heat, the two dissimilar metals expand at different rates,
- the resulting bending is utilized to determine the value of the temperature change.
- This simplicity makes the bimetallic strip an ideal component for a wide variety of applications.

Bi Metallic Strip

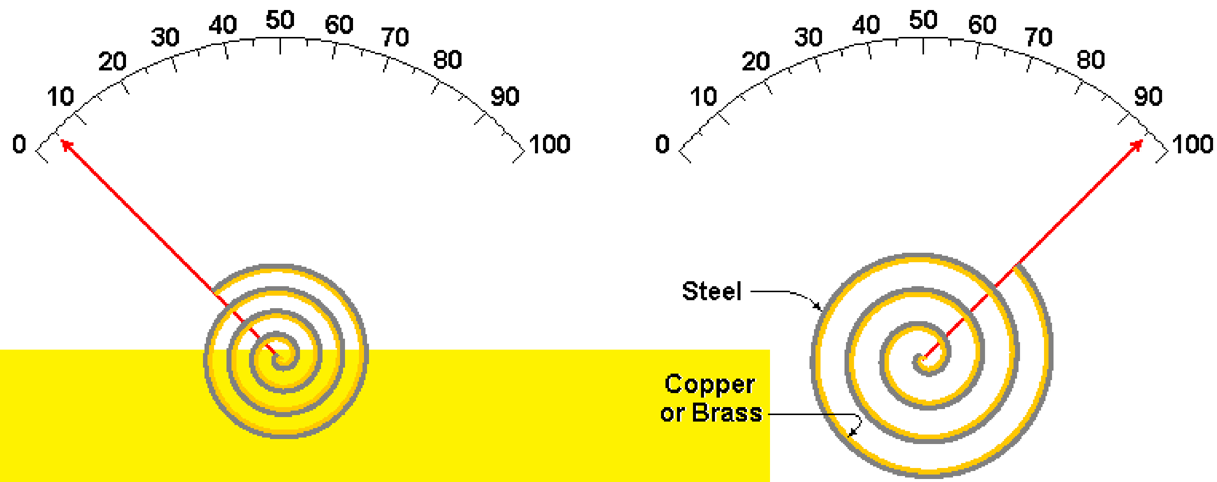


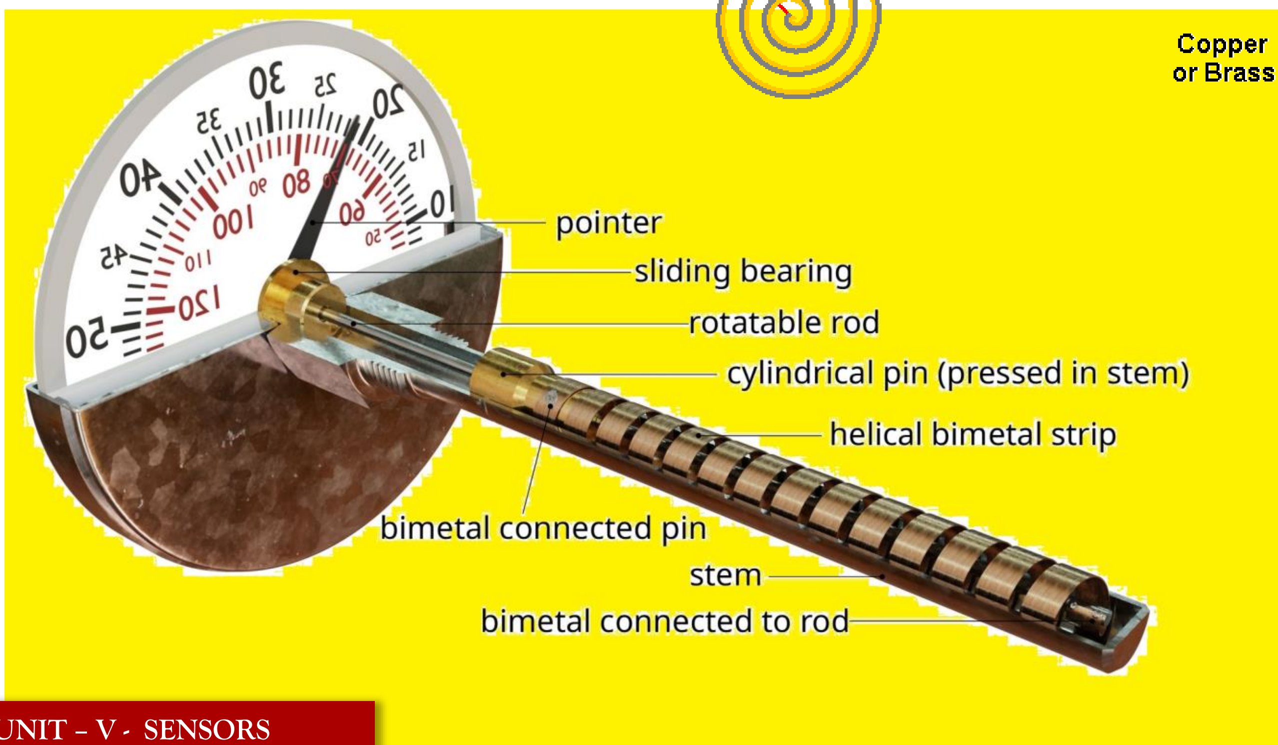




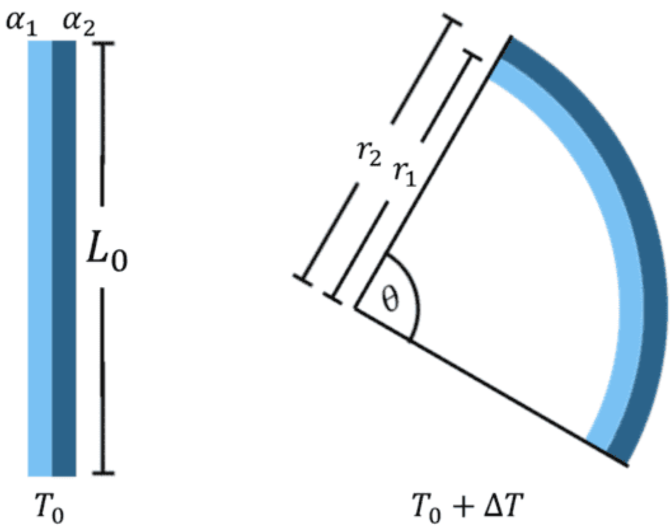
Bimetallic Thermostat

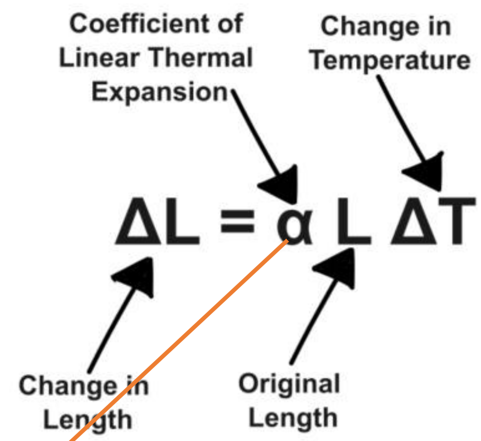
Bi Metallic Strip





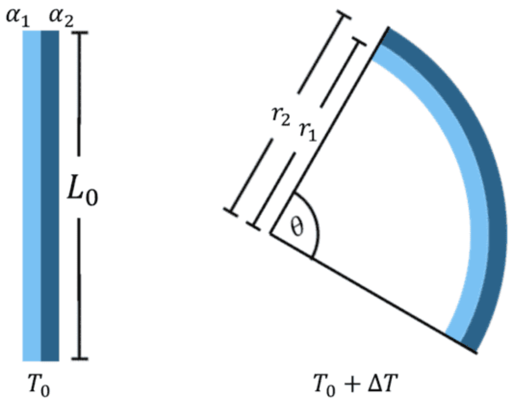
Bi Metallic Strip





Material	Thermal Coefficient of Expansion Per °C	Modulus of Elasticity	
		psi	GN/m^2
Invar	1.7×10^{-6}	21.4×10^6	147
Yellow brass	2.02×10^{-5}	14.0×10^6	96.5
Monel 400	1.35×10^{-5}	26.0×10^6	179
Inconel 702	1.25×10^{-5}	31.5×10^6	217
Stainless-steel type 316	1.6×10^{-5}	28×10^6	193

Bi Metallic Strip



$$\boxed{r = \frac{t\{3(1+m)^2 + (1+mn)[m^2 + (1/mn)]\}}{6(\alpha_2 - \alpha_1)(T - T_0)(1+m)^2}}$$

where t = combined thickness of the bonded strip, m or ft

m = ratio of thicknesses of low- to high-expansion materials

n = ratio of moduli of elasticity of low- to high-expansion materials

α_1 = lower coefficient of expansion, per °C

α_2 = higher coefficient of expansion, per °C

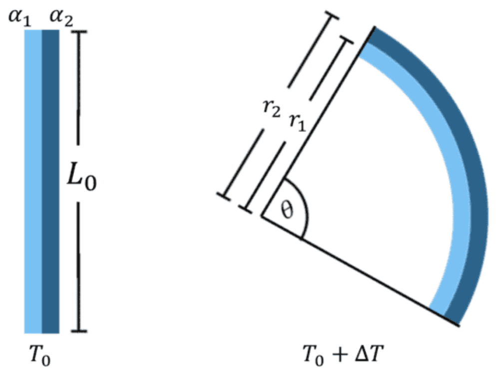
T = temperature, °C

T_0 = initial bonding temperature, °C

Bi Metallic Strip

CURVATURE AND DEFLECTION OF BIMETALLIC STRIP. A bimetallic strip is constructed of strips of yellow brass and Invar bonded together at 30°C. Each has a thickness of 0.3 mm. Calculate the radius of curvature when a 6.0-cm strip is subjected to a temperature of 100°C.

$$\boxed{r = \frac{t\{3(1+m)^2 + (1+mn)[m^2 + (1/mn)]\}}{6(\alpha_2 - \alpha_1)(T - T_0)(1+m)^2}}$$



$$T - T_0 = 100 - 30 = 70°\text{C}$$

$$m = 1.0$$

$$n = \frac{147}{96.5} = 1.52$$

$$\alpha_1 = 1.7 \times 10^{-6}\,°\text{C}^{-1} \qquad \alpha_2 = 2.02 \times 10^{-5}\,°\text{C}^{-1}$$

$$t = (2)(0.3 \times 10^{-3}) = 0.6 \times 10^{-3}\ \text{m}$$

$$r = \frac{(0.6 \times 10^{-3})[(3)(2)^2 + (1 + 1.52)(1 + 1/1.52)]}{6(2.02 - 0.17)(10^{-5})(70)(2)^2}$$

$$= 0.132\ \text{m}$$