Mastering Physics

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Thermal Expansion

As the temperature changes, the length of a material changes.

$$\Delta L = \alpha L_0 \Delta T$$

α is the coefficient of linear expansion and is a constant for the material

ΔL is the change in length

ΔT is the change in temperature

$$L = L_0(1 + \alpha \Delta T)$$

L is the new length

For a particular temperature T, α is found by taking the limit as $\Delta T \rightarrow 0$.

$$\alpha = \frac{\lim}{\Delta T \rightarrow 0} \frac{\Delta L / L}{\Delta T}$$

where $L_0 \approx L$

Some values of α are:

Al	2.4×10^{-5} K^{-1}
glass	0.4-0.9×10^{-5} K^{-1}
quartz (fused)	0.04×10^{-5} K^{-1}

Would want something like quartz (or better) for a telescope mirror.

21-4 THERMAL EXPANSION

You can often loosen a tight metal jar lid by holding it under a stream of hot water. As its temperature rises, the metal lid expands slightly relative to the glass of the jar. Thermal expansion is not always desirable, as Fig. 21-6 suggests. Roadways of bridges usually include expansion slots to allow for changes in length of the roadway as the temperature changes.

Pipes at refineries often include an expansion loop, so that the pipe will not buckle as the temperature rises. Materials used for dental fillings have expansion properties similar to those of tooth enamel. In aircraft manufacture, rivets and other fasteners are often designed so that they are to be cooled in dry ice before insertion and then allowed to ex-

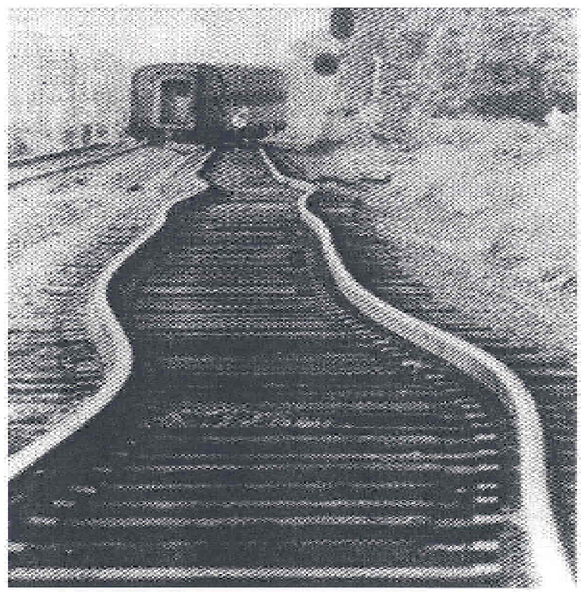

FIGURE 21-6. Railroad tracks distorted because of thermal expansion on a very hot day. Railroad tracks today come in 1500-ft lengths and, to prevent buckling, are laid at or near the maximum annual temperature of the locality.

Note: Not all materials expand with increasing temperature.

i.e. α is not always positive.

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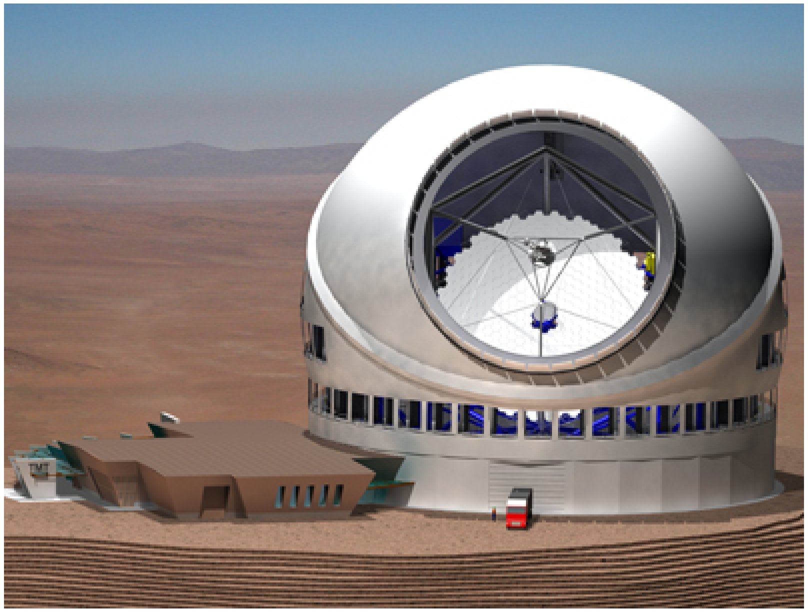
SR-71

Fig. 17.11

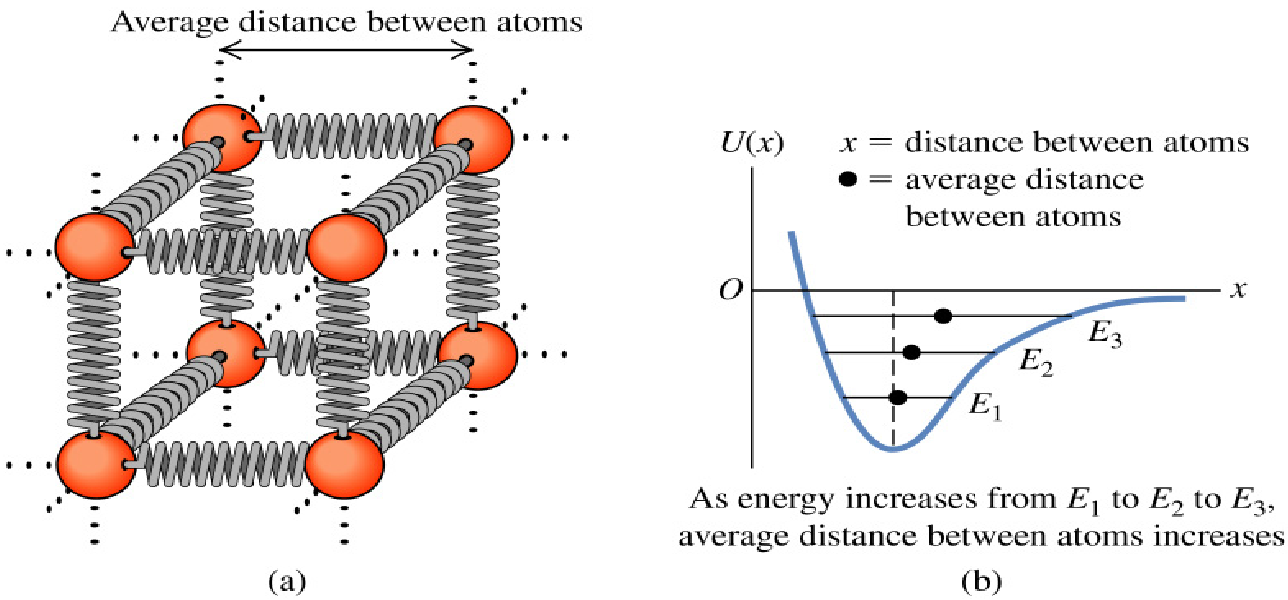


Thirty metre telescope (TMT)

Twim 10 m Keck telescopes
on Mauna Kea

Want to have material for a mirror which has a low
coefficient of expansion.

Understanding thermal expansion



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As T increases, E increases (E_3>E_2>E_1) and the average value of the distance Δx (black dot) over which the atom oscillates increases. Hence the material expands.

The expansion formula just given is for a change in length. However, area and volume also change. These changes can be derived using the linear formula.

Coefficient of volume expansion is defined in a way similar to linear expansion.

$$\beta = \lim_{\Delta T \to 0} \frac{\Delta V / V}{\Delta T} = \frac{1}{V}\frac{dV}{dT}$$

Consider a box with sides L_1, L_2, and L_3.
At a given T, $V=L_1L_2L_3$. The rate of change of volume with temperature

$$\frac{dV}{dT} = L_1L_2\frac{dL_3}{dT} + L_1L_3\frac{dL_2}{dT} + L_2L_3\frac{dL_1}{dT}$$

Divide each side by V

$$\frac{1}{V}\frac{dV}{dT} = \beta = \frac{1}{L_3}\frac{dL_3}{dT} + \frac{1}{L_2}\frac{dL_2}{dT} + \frac{1}{L_1}\frac{dL_1}{dT} = 3\alpha$$

Hence $\beta = 3\alpha$

Similarly, $\Delta A = 2\alpha\Delta T$

Some values of β are: Al 7.2x10^{-5} K^{-1}
glass 1.2-2.7x10^{-5} K^{-1}
quartz (fused) 0.12x10^{-5} K^{-1}

Thermal expansion of water.

Why do lakes freeze only at the top?
Water has a negative coefficient of thermal expansion for the temperature range $0°C \rightarrow 4°C$.

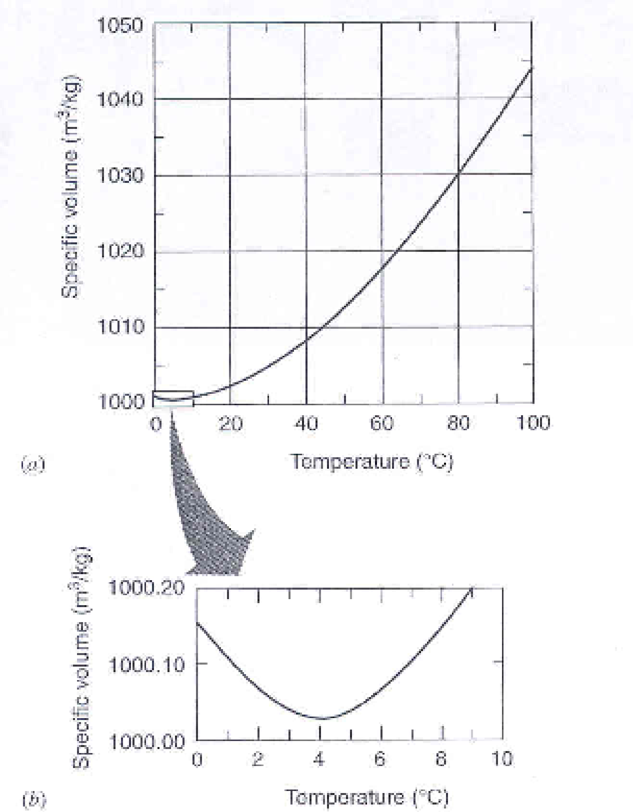
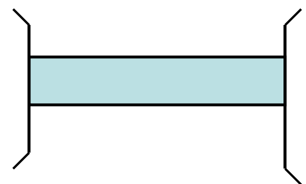


FIGURE 21-11. (*a*) The specific volume (the volume occupied by a particular mass) of water as a function of its temperature. The specific volume is the inverse of the density (the mass per unit volume). (*b*) An enlargement of the region near 4°C, showing a minimum specific volume (or a maximum density).

Recall the basic expansion formulae.

$$\boxed{\begin{aligned}\Delta L &= \alpha L \Delta T \\ \Delta A &= 2\alpha A \Delta T \\ \Delta V &= 3\alpha V \Delta T = \beta V \Delta T\end{aligned}}$$

<u>Thermal Stress and Strain</u> (read sections 11.4 and 11.5)



A rod is clamped at two rigid ends. Under heating or cooling, the rod will want to expand or contract.

Hooke's law: $\dfrac{Stress}{Strain} =$ (Elastic modulus)

Linear stress and strain:

$\dfrac{F_\perp}{A} = -Y \dfrac{\Delta L}{L}$ Y is Young's modulus= $\dfrac{Stress}{Strain}$

If ΔT is negative, $\dfrac{F_\perp}{A}$ is positive.

Bulk Stress and Strain

$$\frac{F_\perp}{A} = \Delta p = -B\frac{\Delta V}{V}$$ B is the bulk modulus.

(-) because Δp and ΔV have opposite signs.

Some values of Y and B.

	Y (Pa)	B (Pa)
Copper	11×10^{10}	14×10^{10}
Lead	1.6×10^{10}	4.1×10^{10}
Steel	20×10^{10}	16×10^{10}

Problem

Steel train rails are laid in 12.0 m long segments placed end-to-end. The rails are laid on a winter day when their temperature is $-2°C.$

(a) How much space must be left between adjacent rails if they are to just touch when their temperature is $33°C$?

(b) If the rails are originally laid in contact, what is the stress in them on a summer day when their temperature is $33°C$?

Heat (Q)

Heat is energy, specifically the energy transferred from one object to another solely due to a temperature difference. The transfer is called heat flow.

Units for heat
1 cal = 4.186 J
1 kcal = 1000 cal (note: the food calorie is the kcal).
1 Btu = 1055 J

How much heat, Q, is required to change the temperature by ΔT?

Q=mcΔT c=specific heat of the material.

Total mass m=nM where n=number of moles.
So Q=nMcΔT where M is the molecular weight.
or Q=nCΔT where C=Mc is the molar heat capacity.

Some values

Substance	c (J/kg.K)	M (kg/mole)	C (J/mol.K)
Aluminum	910	0.0270	24.6
Silver	234	0.108	25.3
Ice ($\approx 0°C$)	2100	0.018	37.8
Water	4186	0.018	75.4

Note 1. C for most elemental solids is ~25J/mol.K (Dulong and Petit)
Note 2. Water has a very large specific heat.

For gases, we distinguish between c_v (specific heat at constant volume), and c_p (specific heat at constant pressure).