Thermodynamics: An Engineering Approach
8th Edition
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Topic 1
INTRODUCTION

Objectives

- Identify the unique vocabulary associated with thermodynamics through the precise definition of basic concepts to form a sound foundation for the development of the principles of thermodynamics.
- Review the metric SI and the English unit systems.
- Explain the basic concepts of thermodynamics such as system, state, state postulate, equilibrium, process, and cycle.
- Review concepts of temperature, temperature scales, pressure, and absolute and gauge pressure.
- Introduce an intuitive systematic problem-solving technique.

THERMODYNAMICS AND ENERGY

- **Thermodynamics**: The science of *energy.*
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.

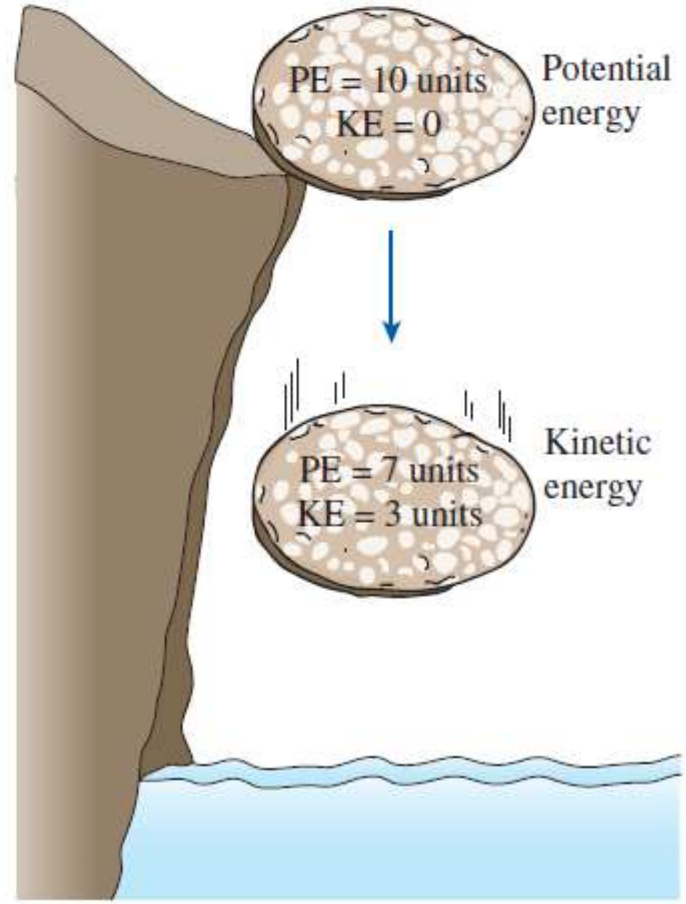

FIGURE 1–1
Energy cannot be created or destroyed; it can only change forms (the first law).

- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.
- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- It provides a direct and easy way to the solution of engineering problems and it is used in this text.
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles.
- It is used in this text only in the supporting role.

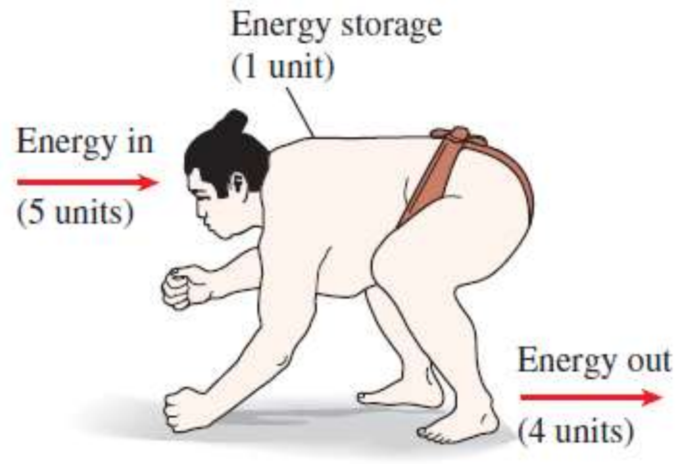

FIGURE 1–2
Conservation of energy principle for the human body.

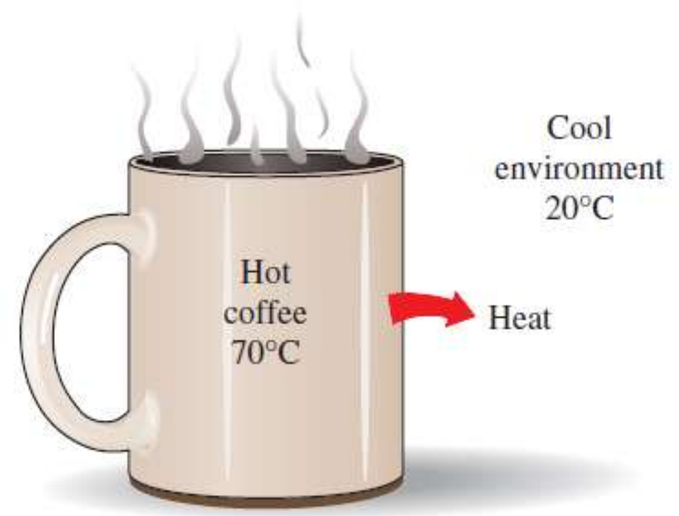

FIGURE 1–3
Heat flows in the direction of decreasing temperature.

Application Areas of Thermodynamics

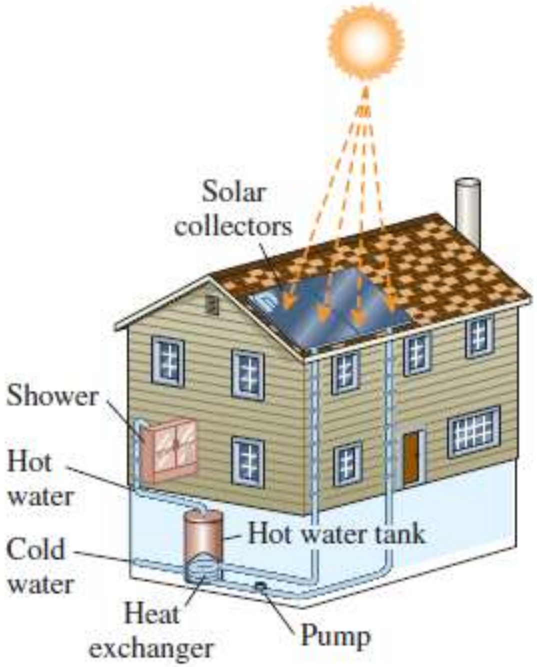

FIGURE 1–4

The design of many engineering systems, such as this solar hot water system, involves thermodynamics.

Refrigerator

© McGraw-Hill Education, Jill Braaten

Boats

© Doug Menuez/Getty Images RF

Aircraft and spacecraft

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Power plants

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All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.

Human body

© Ryan McVay/Getty Images RF

Cars

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Wind turbines

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Food processing

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A piping network in an industrial facility.

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IMPORTANCE OF DIMENSIONS AND UNITS

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as mass *m*, length *L*, time *t*, and temperature *T* are selected as **primary** or **fundamental dimensions**, while others such as velocity *V*, energy *E*, and volume *V* are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.
- **Metric SI system**: A simple and logical system based on a decimal relationship between the various units.
- **English system**: It has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

TABLE 1–1

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

TABLE 1–2

Standard prefixes in SI units

Multiple	Prefix
10^{24}	yotta, Y
10^{21}	zetta, Z
10^{18}	exa, E
10^{15}	peta, P
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p
10^{-15}	femto, f
10^{-18}	atto, a
10^{-21}	zepto, z
10^{-24}	yocto, y

Some SI and English Units

$$1 \text{ lbm} = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$

$$\text{Force} = (\text{Mass})(\text{Acceleration})$$

$$F = ma$$

$$1 \text{ N} = 1 \text{ kg}\cdot\text{m/s}^2$$

$$1 \text{ lbf} = 32.174 \text{ lbm}\cdot\text{ft/s}^2$$

Work = Force × Distance

1 J = 1 N·m

1 cal = 4.1868 J

1 Btu = 1.0551 kJ

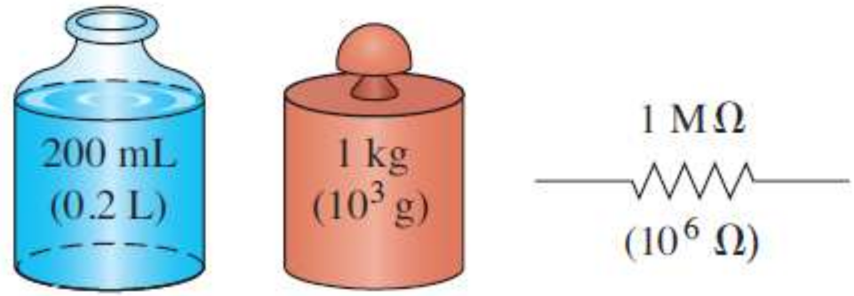


FIGURE 1–6
The SI unit prefixes are used in all branches of engineering.

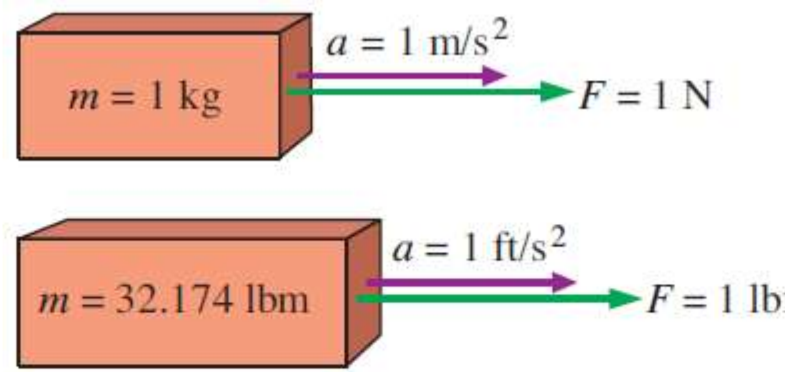


FIGURE 1–7
The definition of the force units.

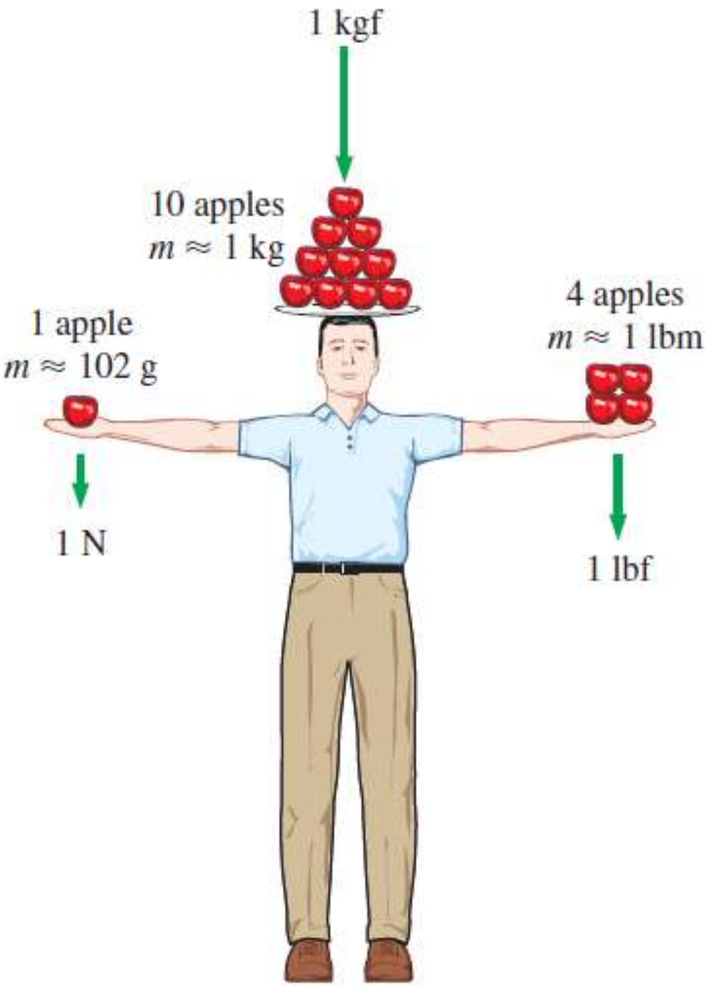


FIGURE 1–8
The relative magnitudes of the force units newton (N), kilogram-force (kgf), and pound-force (lbf).

FIGURE 1–9
A body weighing 150 lbf on earth will weigh only 25 lbf on the moon.

$$W = mg \quad \text{(N)}$$

W weight
m mass
g gravitational acceleration

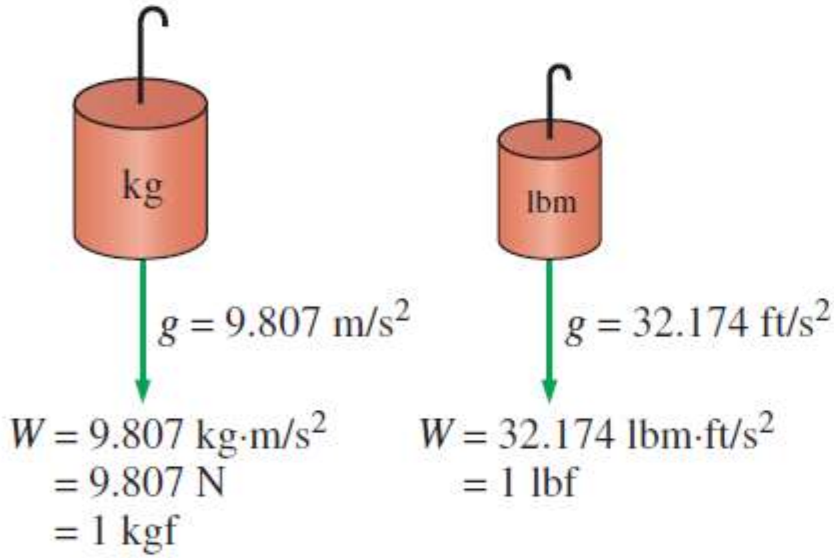


FIGURE 1–10
The weight of a unit mass at sea level.

FIGURE 1–11
A typical match yields about one Btu (or one kJ) of energy if completely burned.

Specific weight γ: The weight of a unit volume of a substance.

$$\gamma = \rho g$$

Dimensional homogeneity

All equations must be dimensionally **homogeneous**.

Unity Conversion Ratios

All nonprimary units (secondary units) can be formed by combinations of primary units.
Force units, for example, can be expressed as

$$\mathrm{N} = \mathrm{kg}\,\frac{\mathrm{m}}{\mathrm{s}^2} \quad \text{and} \quad \mathrm{lbf} = 32.174\ \mathrm{lbm}\,\frac{\mathrm{ft}}{\mathrm{s}^2}$$

They can also be expressed more conveniently as **unity conversion ratios** as

$$\frac{\mathrm{N}}{\mathrm{kg}\cdot\mathrm{m/s}^2} = 1 \quad \text{and} \quad \frac{\mathrm{lbf}}{32.174\ \mathrm{lbm}\cdot\mathrm{ft/s}^2} = 1$$

Unity conversion ratios are identically equal to 1 and are unitless, and thus such ratios (or their inverses) can be inserted conveniently into any calculation to properly convert units.

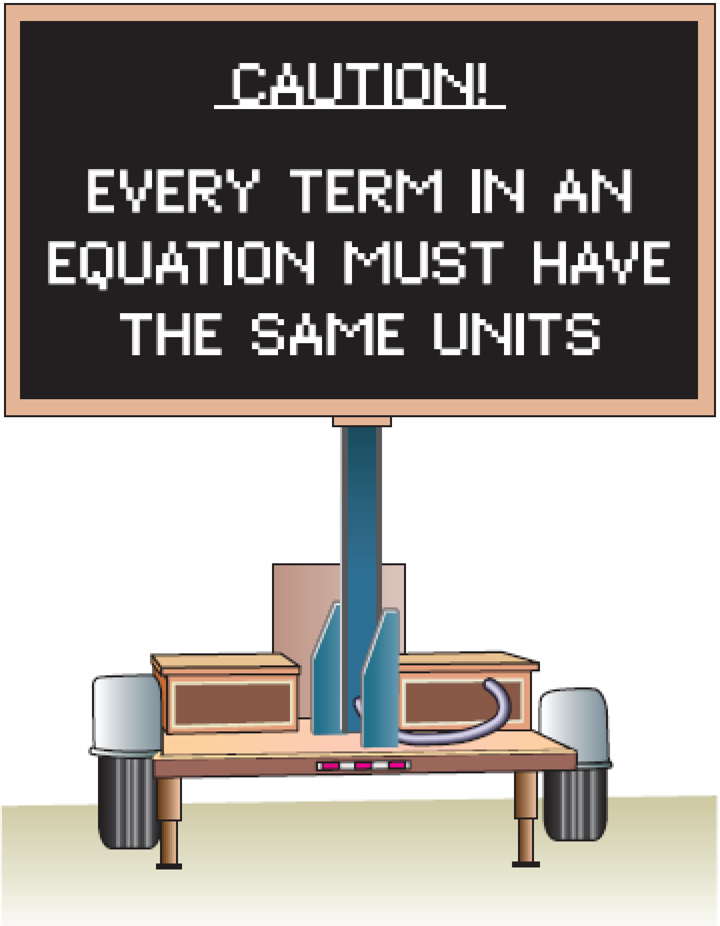


FIGURE 1–14
Always check the units in your calculations.

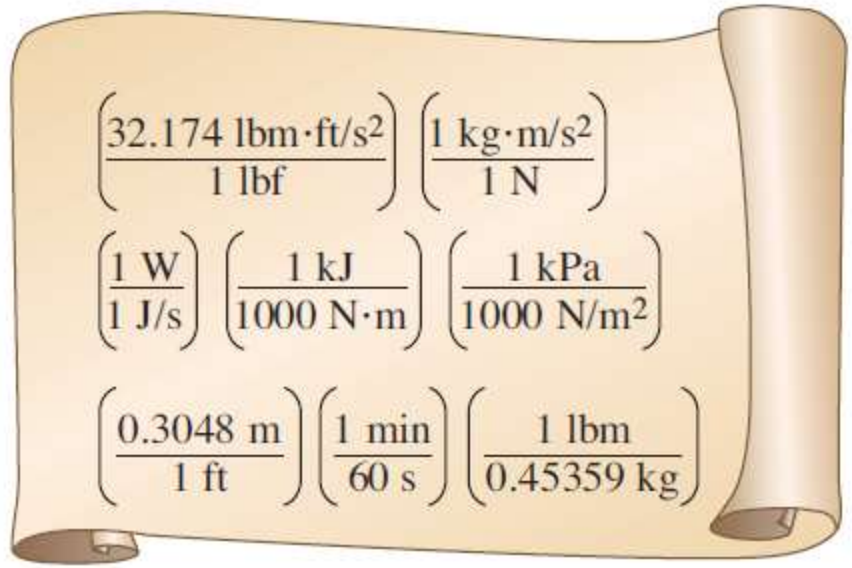


FIGURE 1–15
Every unity conversion ratio (as well as its inverse) is exactly equal to one. Shown here are a few commonly used unity conversion ratios.

FIGURE 1–16
A mass of 1 lbm weighs 1 lbf on earth.

$$W = mg = (453.6\ \text{g})(9.81\ \text{m/s}^2)\left(\frac{1\ \text{N}}{1\ \text{kg·m/s}^2}\right)\left(\frac{1\ \text{kg}}{1000\ \text{g}}\right) = 4.49\ \text{N}$$

FIGURE 1–17
A quirk in the metric system of units.

Mass and Weight Example

A Lunar Roving Vehicle (LRV) was used on the moon in the last three missions of the Apollo program (Apollo 15, 16, and 17). The LRV weighed 463 lbf on Earth. What is its mass on Earth in pounds-mass? In kilograms? What is its weight on Earth in Newtons? If the weight of the LRV on the Moon is 77 lbf, what is its mass on the Moon? What is the gravity on the Moon (in ft/s^2 and m/s^2)? What is the weight on the Moon in Newtons?

Solution

DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\mathrm{kg/m^3})$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$\mathrm{SG} = \frac{\rho}{\rho_{\mathrm{H_2O}}}$$

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\mathrm{N/m^3})$$

$V = 12\ \mathrm{m^3}$
$m = 3\ \mathrm{kg}$

$\rho = 0.25\ \mathrm{kg/m^3}$
$v = \dfrac{1}{\rho} = 4\ \mathrm{m^3/kg}$

Density is mass per unit volume; specific volume is volume per unit mass.

TABLE 1–3

Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact*.

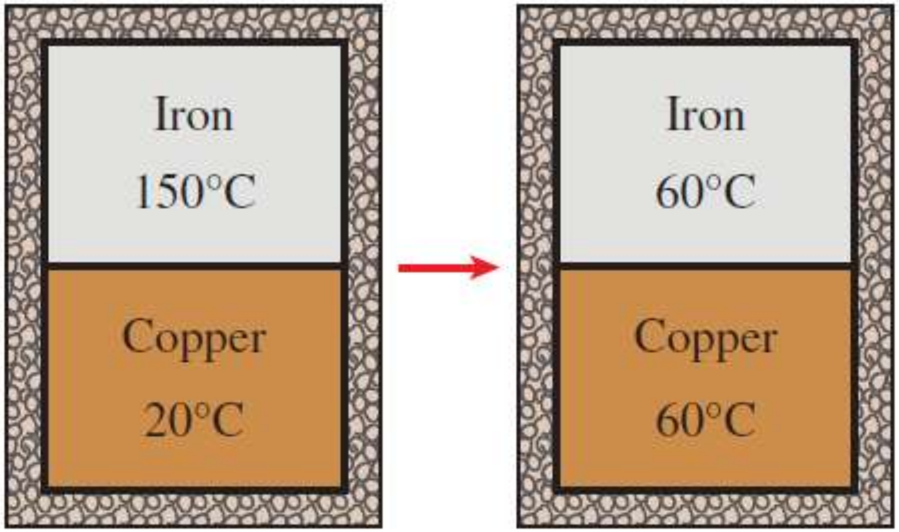


FIGURE 1–34
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- **Ice point**: A mixture of ice and water that is in equilibrium with air saturated with vapor at 1 atm pressure (0°C or 32°F).
- **Steam point**: A mixture of liquid water and water vapor (with no air) in equilibrium at 1 atm pressure (100°C or 212°F).
- **Celsius scale**: in SI unit system
- **Fahrenheit scale**: in English unit system
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI) **Rankine scale** (E)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.

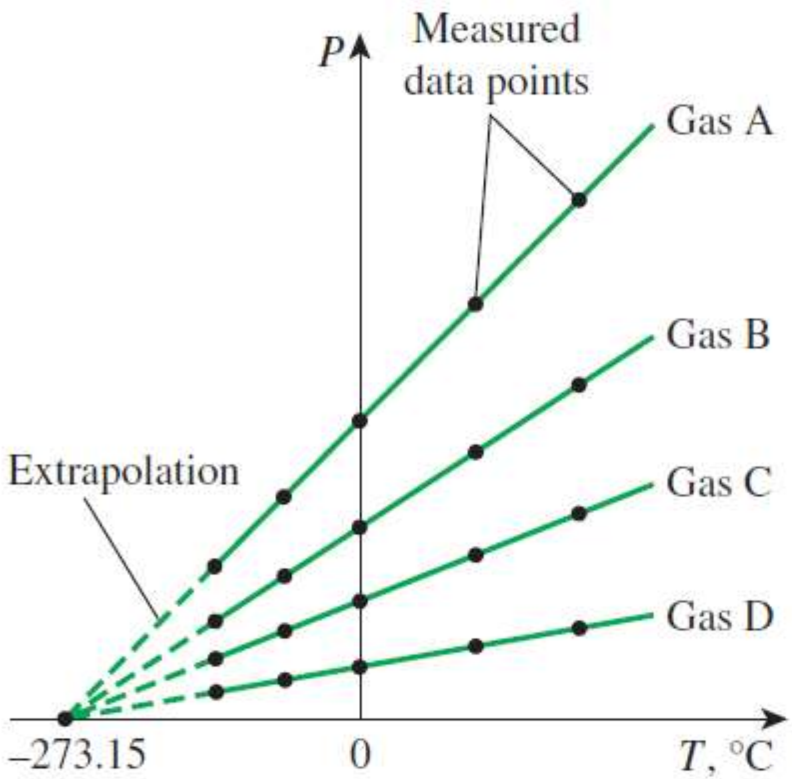


FIGURE 1–35

P versus T plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.

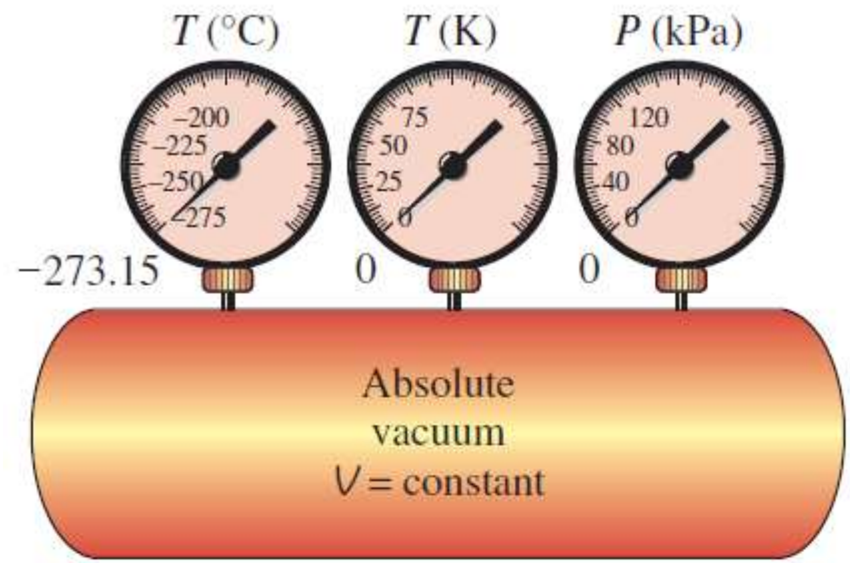


FIGURE 1–36

A constant-volume gas thermometer would read $-273.15°C$ at absolute zero pressure.

$$T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273.15$$

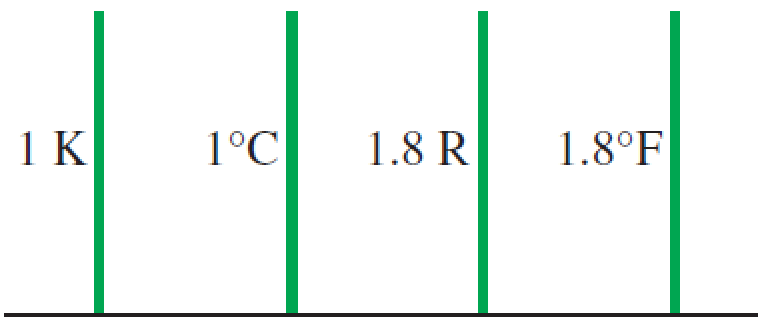
$$T(\mathrm{R}) = T(^\circ\mathrm{F}) + 459.67$$

$$T(\mathrm{R}) = 1.8T(\mathrm{K})$$

$$T(^\circ\mathrm{F}) = 1.8T(^\circ\mathrm{C}) + 32$$

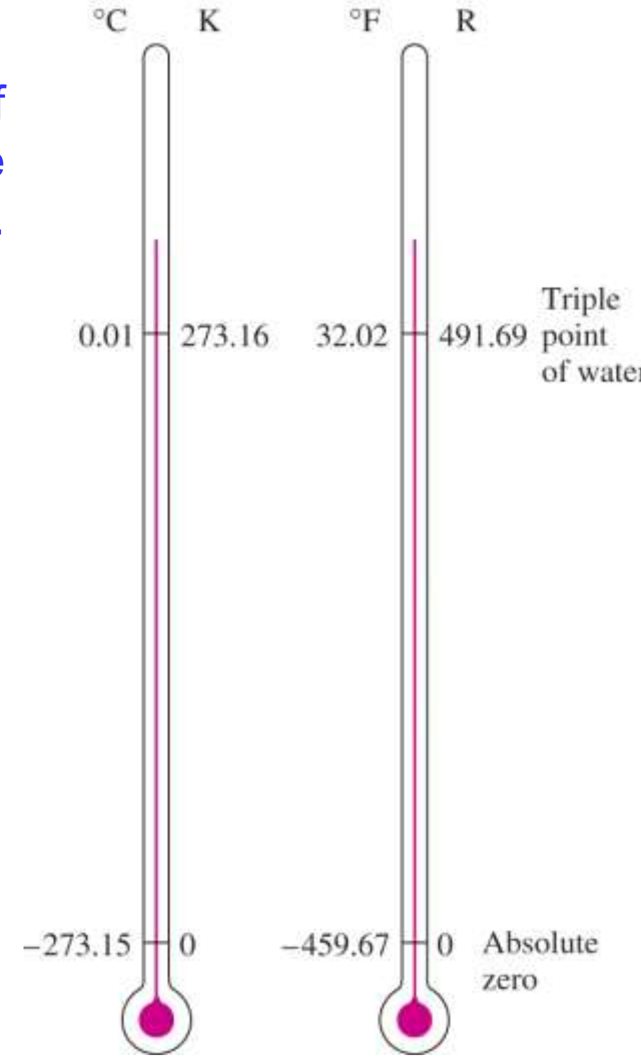
$$\Delta T(\mathrm{K}) = \Delta T(^\circ\mathrm{C})$$

$$\Delta T(\mathrm{R}) = \Delta T(^\circ\mathrm{F})$$



Comparison of magnitudes of various temperature units.

Comparison of temperature scales.



- The reference temperature in the original Kelvin scale was the ***ice point***, 273.15 K, which is the temperature at which water freezes (or ice melts).
- The reference point was changed to a much more precisely reproducible point, the ***triple point*** of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.

The International Temperature Scale of 1990 (ITS-90)

The *International Temperature Scale of 1990* supersedes the International Practical Temperature Scale of 1968 (**IPTS-68**), 1948 (**ITPS-48**), and 1927 (**ITS-27**).

The ITS-90 is similar to its predecessors except that it is more refined with updated values of fixed temperatures, has an extended range, and conforms more closely to the thermodynamic temperature scale.

On this scale, the unit of thermodynamic temperature *T* is again the kelvin (K), defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water, which is sole defining fixed point of both the ITS-90 and the Kelvin scale and is the most important thermometric fixed point used in the calibration of thermometers to ITS-90. The unit of Celsius temperature is the degree Celsius (°C).

The ice point remains the same at 0°C (273.15 K) in both ITS-90 and ITPS-68, but the steam point is 99.975°C in ITS-90 whereas it was 100.000°C in IPTS-68.

The change is due to precise measurements made by gas thermometry by paying particular attention to the effect of sorption (the impurities in a gas absorbed by the walls of the bulb at the reference temperature being desorbed at higher temperatures, causing the measured gas pressure to increase).

PRESSURE

Pressure: A normal force exerted by a fluid per unit area

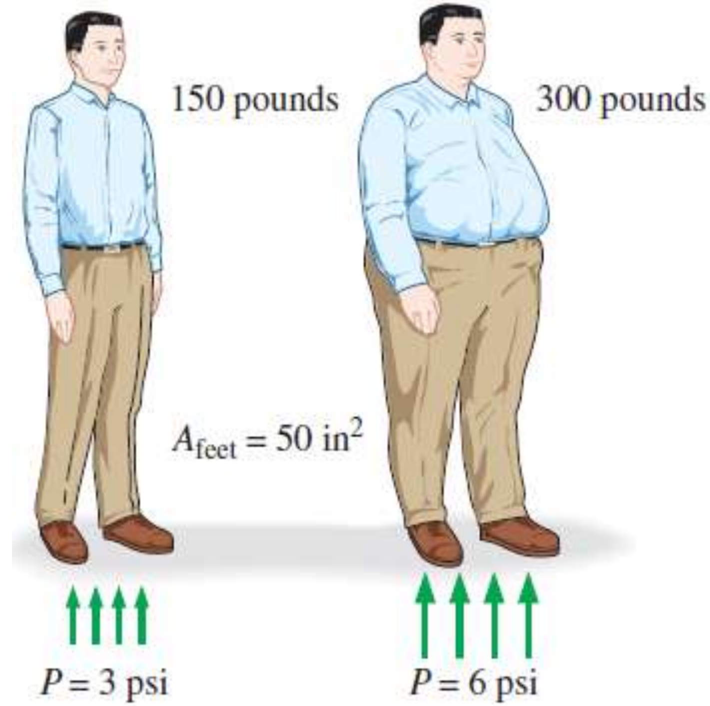
$$1 \text{ Pa} = 1 \text{ N/m}^2$$

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa} = 100 \text{ kPa}$$

$$1 \text{ atm} = 101{,}325 \text{ Pa} = 101.325 \text{ kPa} = 1.01325 \text{ bars}$$

$$\begin{aligned} 1 \text{ kgf/cm}^2 &= 9.807 \text{ N/cm}^2 = 9.807 \times 10^4 \text{ N/m}^2 = 9.807 \times 10^4 \text{ Pa} \\ &= 0.9807 \text{ bar} \\ &= 0.9679 \text{ atm} \end{aligned}$$

Some basic pressure gauges.



$$P = \sigma_n = \frac{W}{A_{feet}} = \frac{150 \text{ lbf}}{50 \text{ in}^2} = 3 \text{ psi}$$

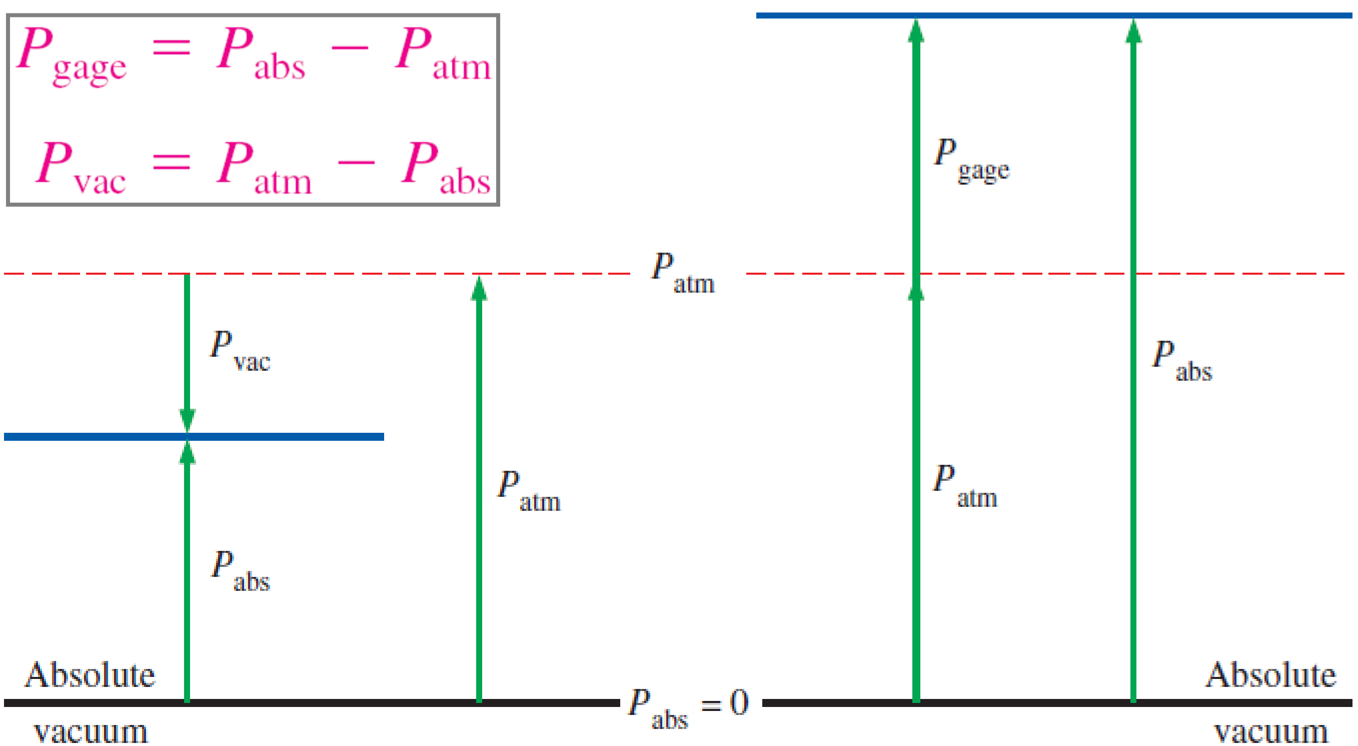
FIGURE 1–39

The normal stress (or "pressure") on the feet of a chubby person is much greater than on the feet of a slim person.

- **Absolute pressure**: The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gauge pressure**: The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gauge pressure.
- **Vacuum pressures**: Pressures below atmospheric pressure.

Throughout this text, the pressure ***P*** will denote ***absolute pressure*** unless specified otherwise.

$$\boxed{\begin{aligned} P_{gage} &= P_{abs} - P_{atm} \\ P_{vac} &= P_{atm} - P_{abs} \end{aligned}}$$



Variation of Pressure with Depth

$$\Delta P = P_2 - P_1 = \rho g\, \Delta z = \gamma_s\, \Delta z$$

$$P = P_{atm} + \rho g h \quad \text{or} \quad P_{gage} = \rho g h$$

When the variation of density with elevation is known

$$\Delta P = P_2 - P_1 = -\int_1^2 \rho g\, dz$$

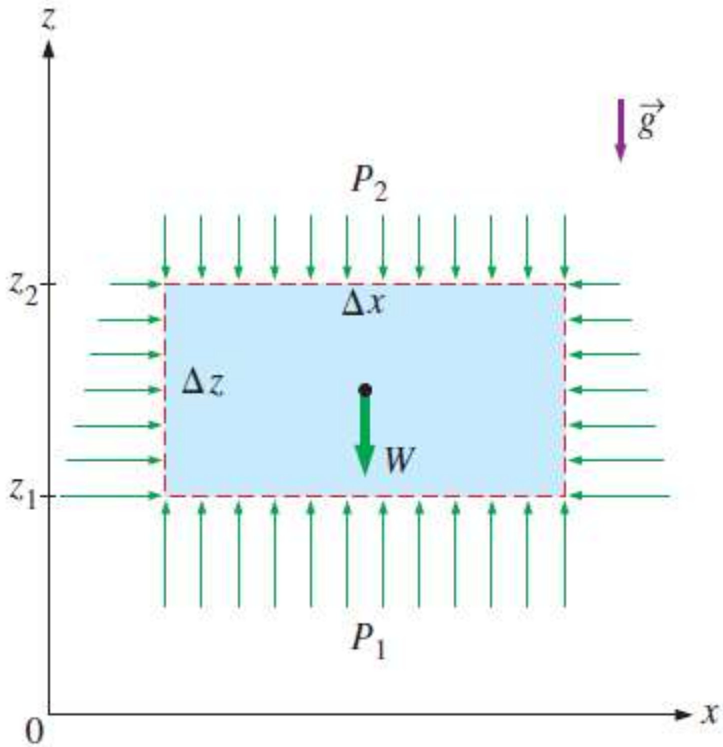


FIGURE 1–43
Free-body diagram of a rectangular fluid element in equilibrium.

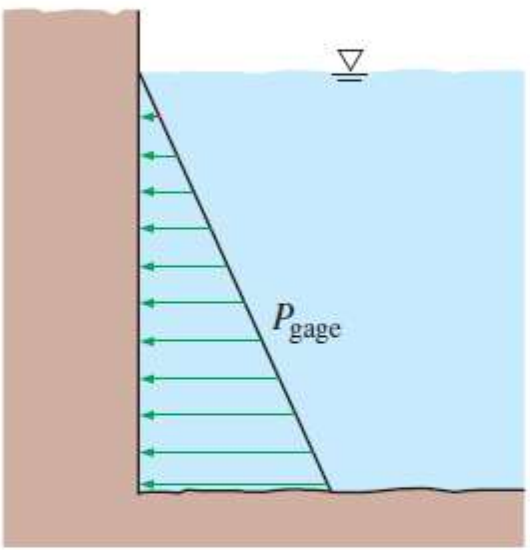


FIGURE 1–42
The pressure of a fluid at rest increases with depth (as a result of added weight).

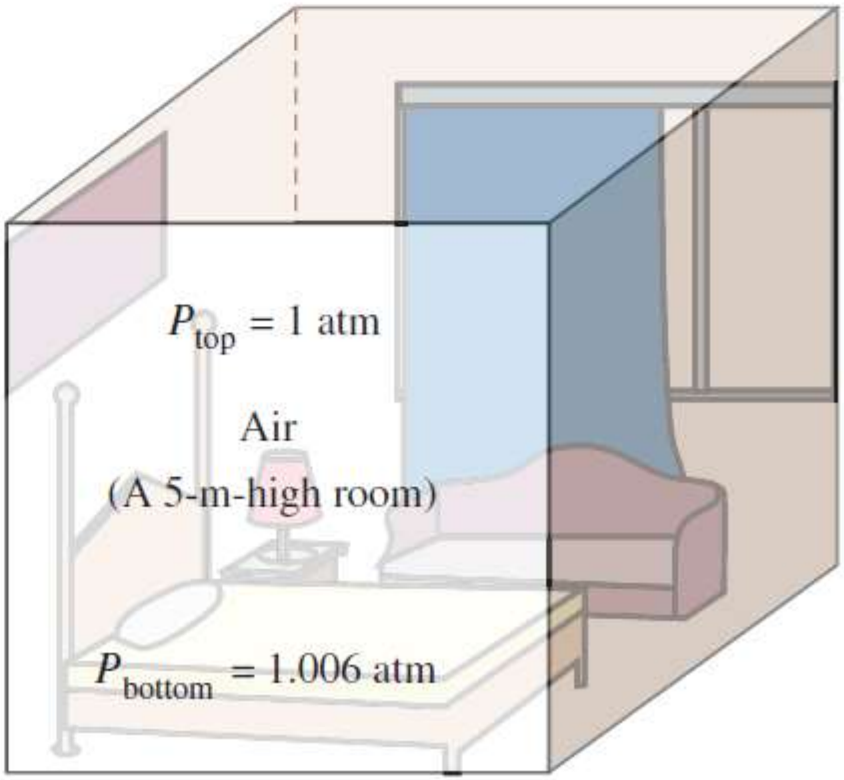


FIGURE 1–44
In a room filled with a gas, the variation of pressure with height is negligible.

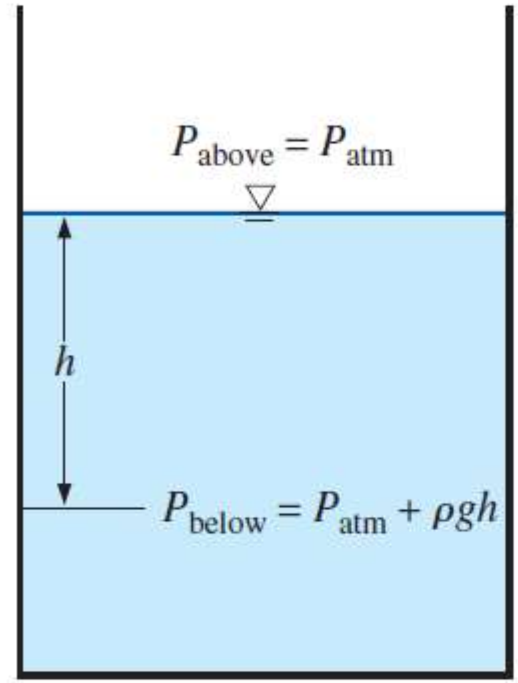
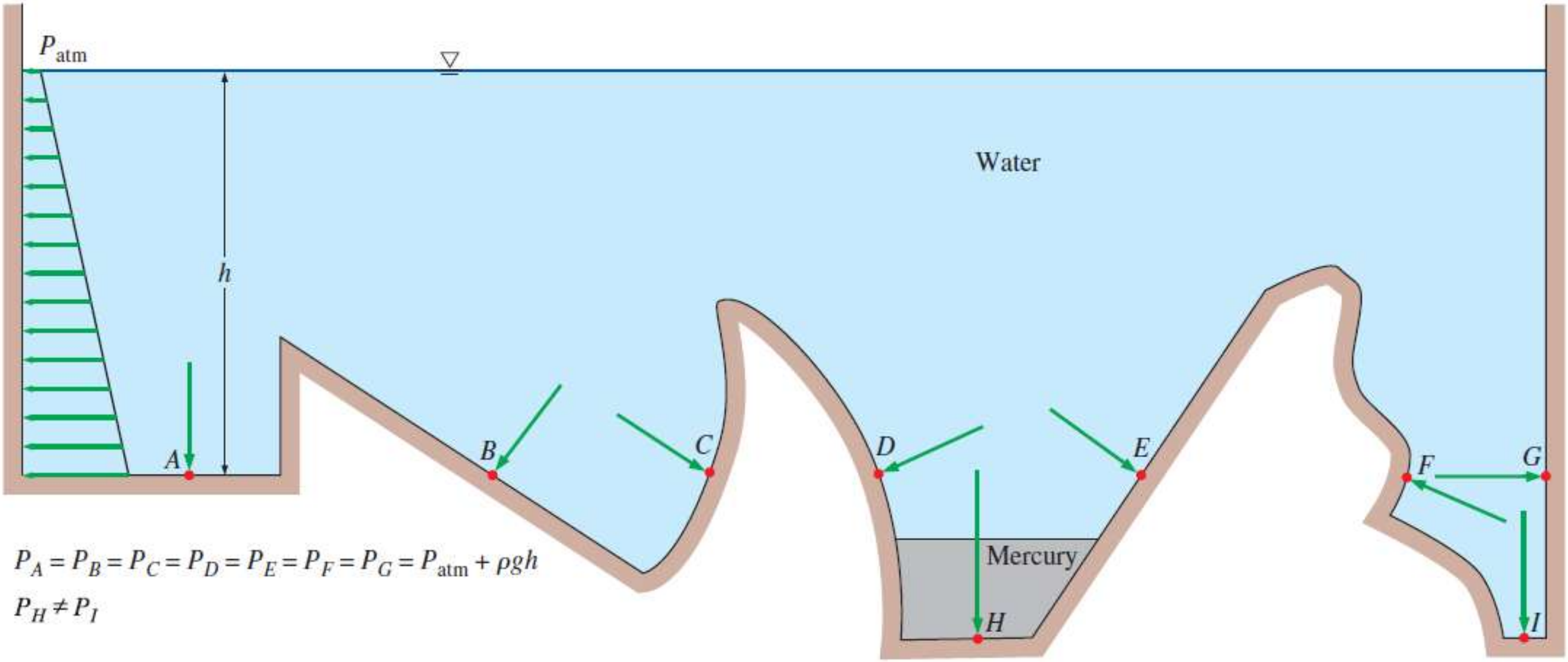


FIGURE 1–45
Pressure in a liquid at rest increases linearly with distance from the free surface.



$P_A = P_B = P_C = P_D = P_E = P_F = P_G = P_{atm} + \rho g h$

$P_H \neq P_I$

FIGURE 1–46

Under hydrostatic conditions, the pressure is the same at all points on a horizontal plane in a given fluid regardless of geometry, provided that the points are interconnected by the same fluid.

Pascal's law: The pressure applied to a confined fluid increases the pressure throughout by the same amount.

$$P_1 = P_2 \quad \rightarrow \quad \frac{F_1}{A_1} = \frac{F_2}{A_2} \quad \rightarrow \quad \frac{F_2}{F_1} = \frac{A_2}{A_1}$$

The area ratio A_2/A_1 is called the *ideal mechanical advantage* of the hydraulic lift.

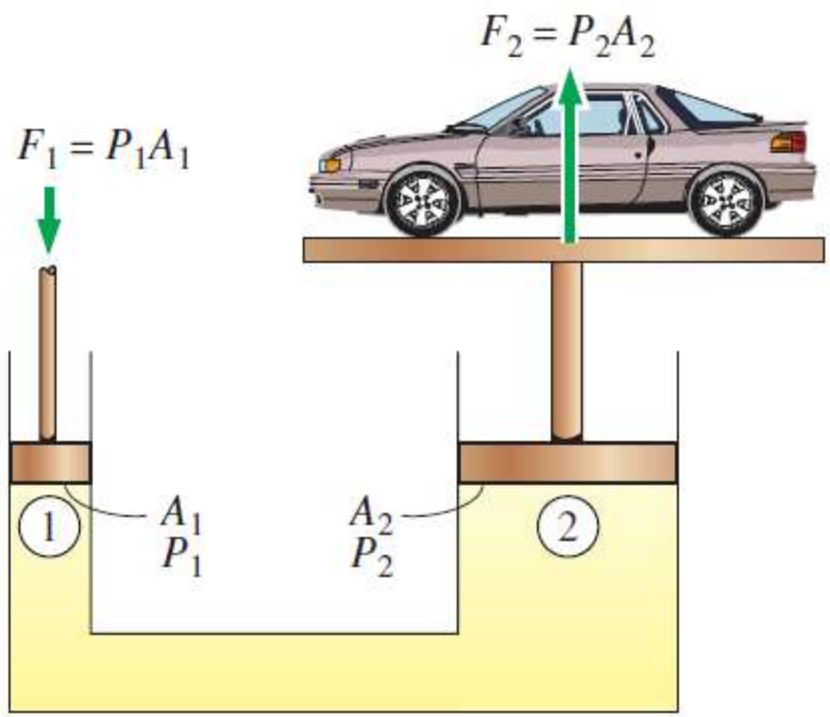


FIGURE 1–47
Lifting of a large weight by a small force by the application of Pascal's law. A common example is a hydraulic jack.

PRESSURE MEASUREMENT DEVICES

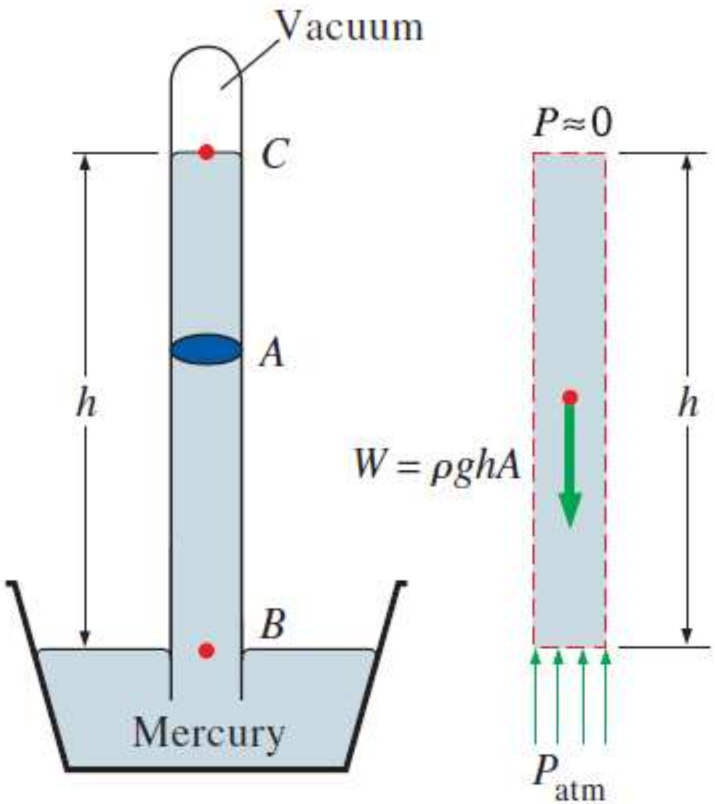


FIGURE 1–48
The basic barometer.

$$P_{atm} = \rho g h$$

The Barometer

- Atmospheric pressure is measured by a device called a **barometer**; thus, the atmospheric pressure is often referred to as the ***barometric pressure***.
- A frequently used pressure unit is the *standard atmosphere*, which is defined as the pressure produced by a column of mercury 760 mm in height at 0°C (ρ_{Hg} = 13,595 kg/m^3) under standard gravitational acceleration (g = 9.807 m/s^2).

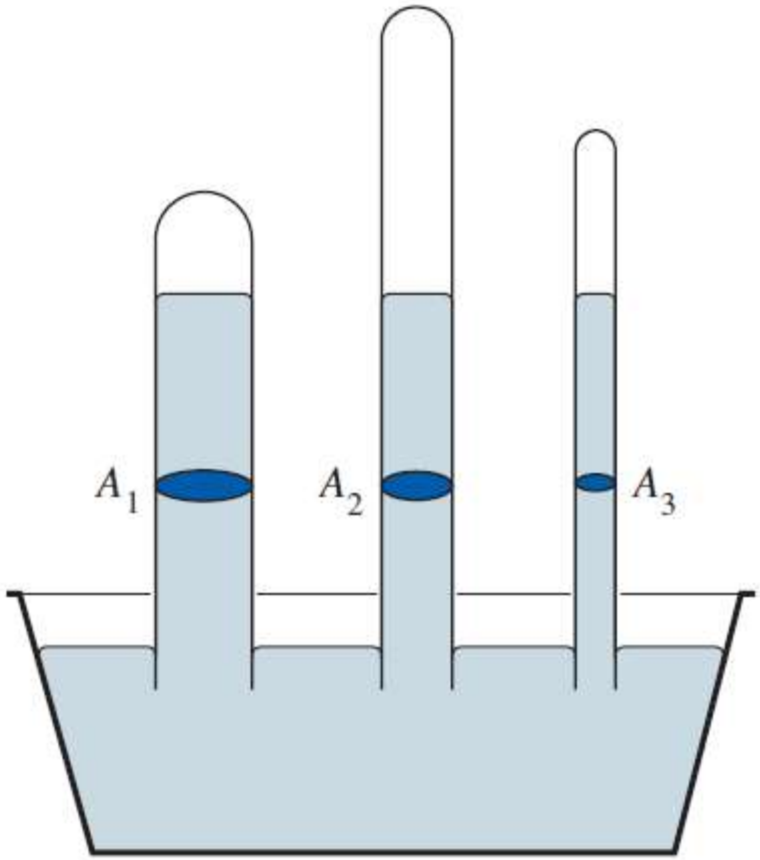


FIGURE 1–49
The length or the cross-sectional area of the tube has no effect on the height of the fluid column of a barometer, provided that the tube diameter is large enough to avoid surface tension (capillary) effects.

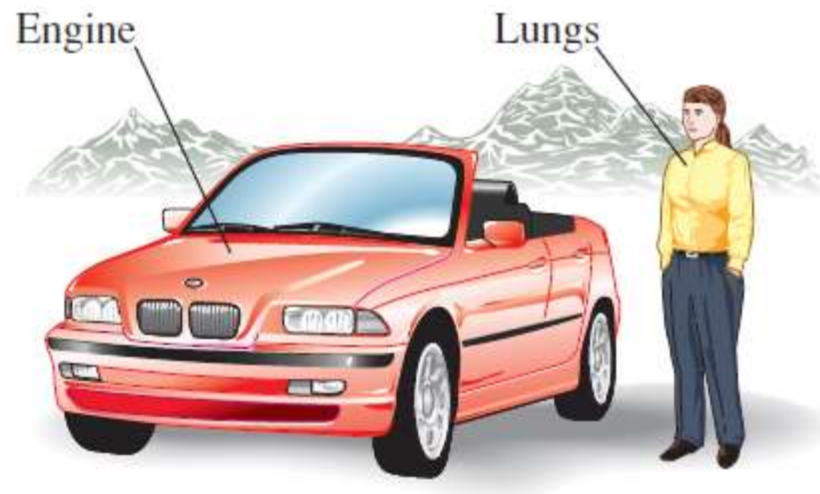
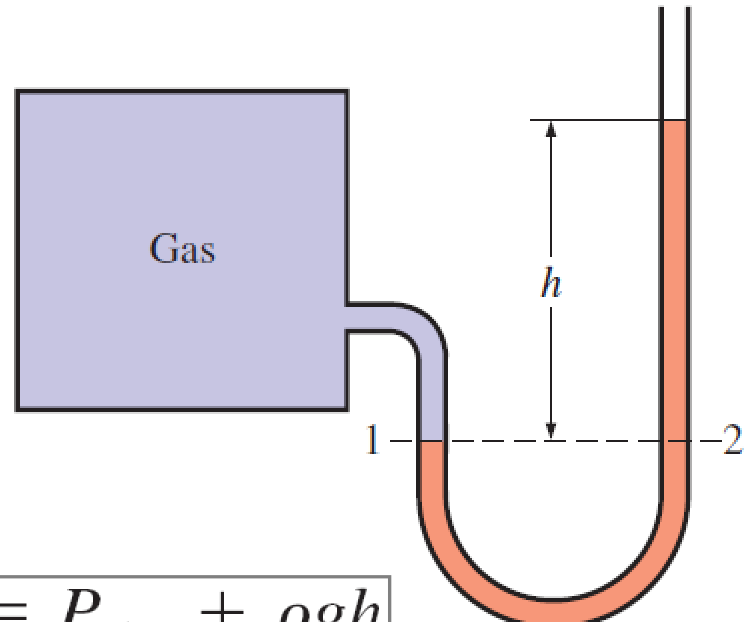


FIGURE 1–50
At high altitudes, a car engine generates less power and a person gets less oxygen because of the lower density of air.

The Manometer

FIGURE 1–54
A simple U-tube manometer, with high pressure applied to the right side.

It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.



$$P_2 = P_{atm} + \rho g h$$

FIGURE 1–55
The basic manometer.

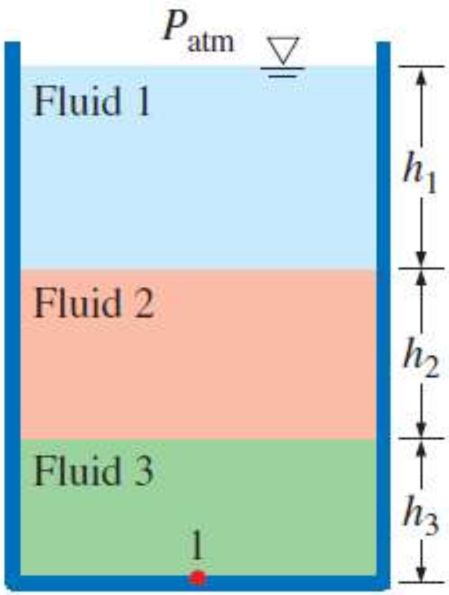


FIGURE 1–57

In stacked-up fluid layers at rest, the pressure change across each fluid layer of density ρ and height h is ρgh.

$$P_{atm} + \rho_1 g h_1 + \rho_2 g h_2 + \rho_3 g h_3 = P_1$$

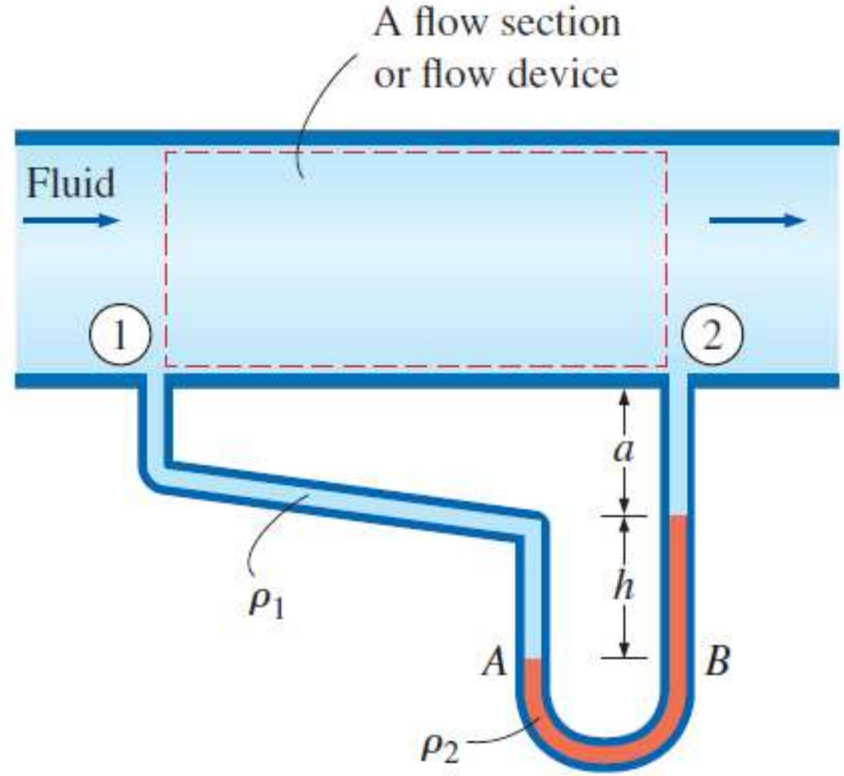


FIGURE 1–58

Measuring the pressure drop across a flow section or a flow device by a differential manometer.

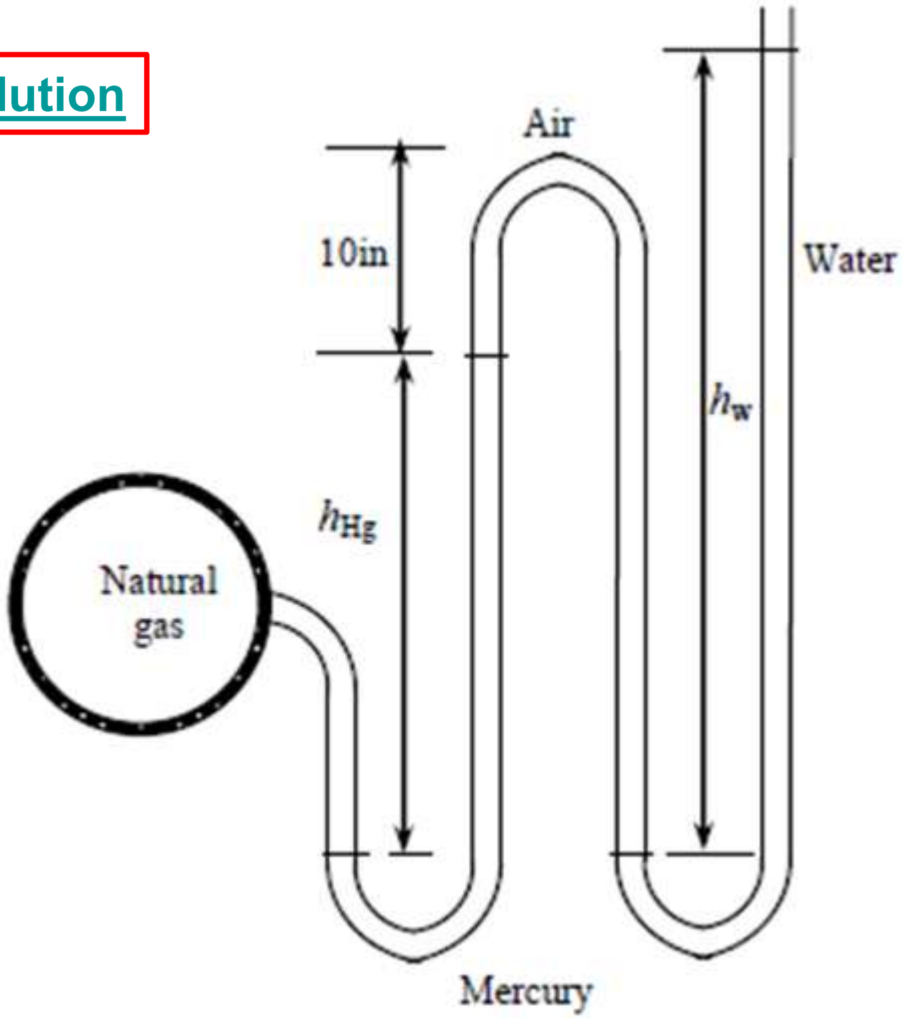
$$P_1 + \rho_1 g(a + h) - \rho_2 gh - \rho_1 ga = P_2$$

$$P_1 - P_2 = (\rho_2 - \rho_1)gh$$

Manometer Example

Determine the absolute and gauge pressure of the natural gas.

Solution



Useful information

ρ_{water} = 62.4lbm/ft^3

SG_{Hg} = 13.6

SG_{air} = 0.0013

P_{atm} = 14.2 psi

h_{Hg} = 6 in

h_{water} = 27 in

lbf =32.2 lbm ft/s^2

Other Pressure Measurement Devices

- **Bourdon tube**: Consists of a hollow metal tube bent like a hook whose end is closed and connected to a dial indicator needle.
- **Pressure transducers**: Use various techniques to convert the pressure effect to an electrical effect such as a change in voltage, resistance, or capacitance.
- Pressure transducers are smaller and faster, and they can be more sensitive, reliable, and precise than their mechanical counterparts.
- **Strain-Gauge pressure transducers:** Work by having a diaphragm deflect between two chambers open to the pressure inputs.
- **Piezoelectric transducers**: Also called solid-state pressure transducers, work on the principle that an electric potential is generated in a crystalline substance when it is subjected to mechanical pressure.

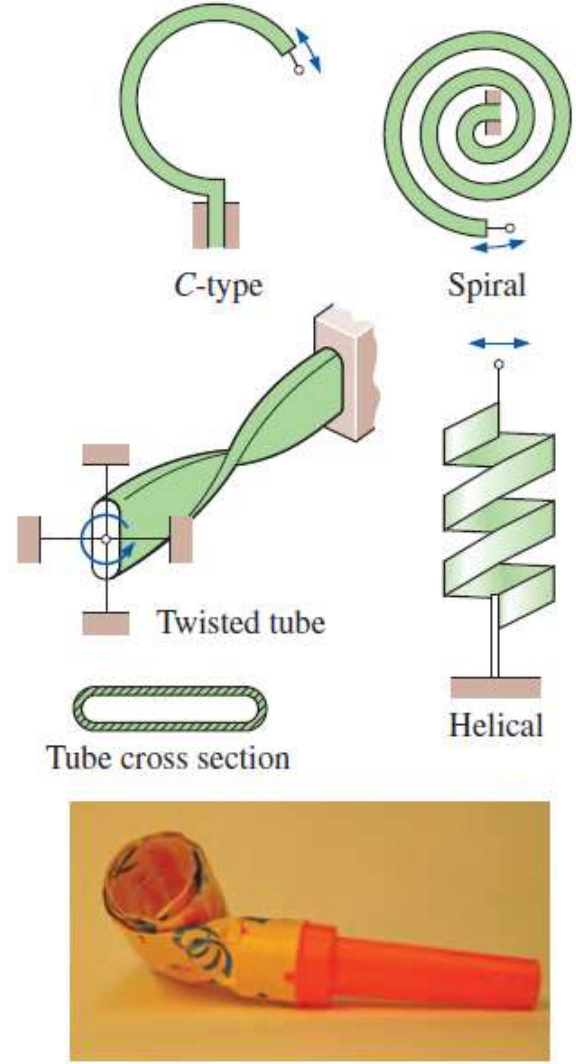


FIGURE 1–60
Various types of Bourdon tubes used to measure pressure. They work on the same principle as party noise-makers (bottom photo) due to the flat tube cross section.

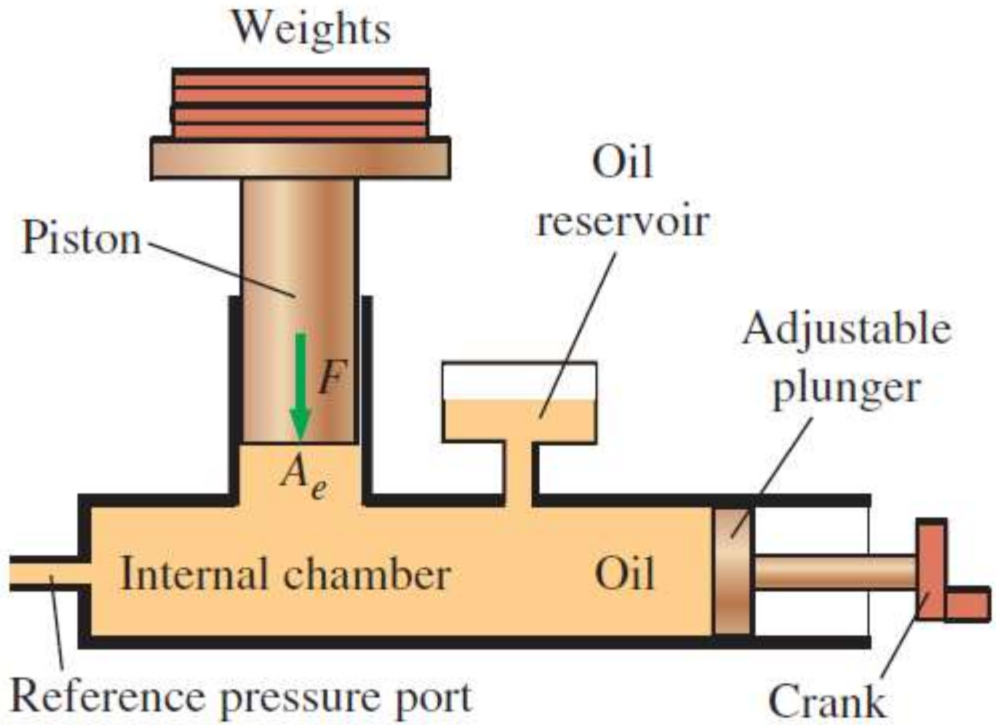


FIGURE 1–61

A deadweight tester is able to measure extremely high pressures (up to 10,000 psi in some applications).

Summary

- Thermodynamics and energy
  - Application areas of thermodynamics
- Importance of dimensions and units
  - Some SI and English units, Dimensional homogeneity, Unity conversion ratios
- Density and specific gravity
- Temperature and the zeroth law of thermodynamics
  - Temperature scales
  - ITS-90
- Pressure
  - Variation of pressure with depth
- The manometer
  - Other pressure measurement devices
- The barometer and atmospheric pressure