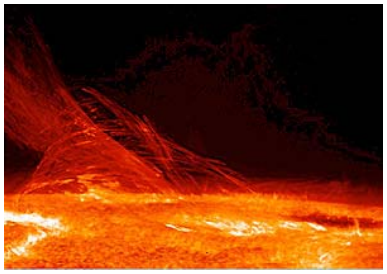
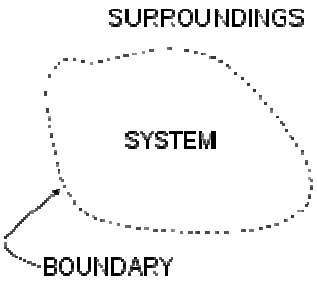


Lecture 4



Heat, Calorimetry, and Energy in Thermal processes

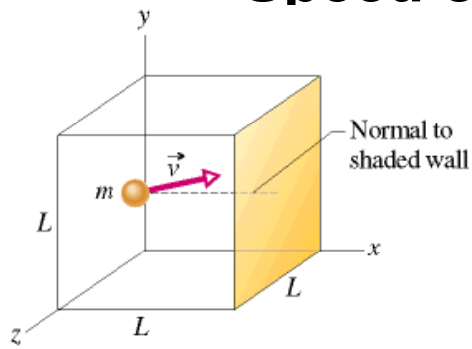
(NJIT Physics, Chapter 11)

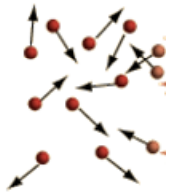
http://web.njit.edu/~sirenko/Phys-103-2005/Phys-103-2012.htm

Physics 103 Spring 2012

Last week: temperature and thermal expansion

Pressure, Temperature, and Speed of molecules





$$v_{rms} = \sqrt{\frac{3RT}{M}}$$

mN_A is the molar mass M

Root-mean-square speed

$$K_{avg} = \frac{1}{2} m v_{avg}^2 \sim T$$

$$K_{avg} = \frac{1}{2} m v_{avg}^2 = \frac{3}{2} k_B T$$

k_B – Boltzman Constant

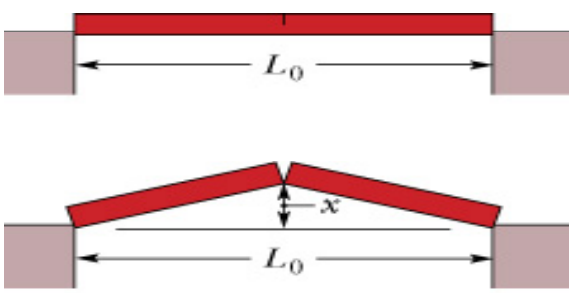
Boltzmann constant = 1.3806503 × 10^{-23} m^2 kg s^{-2} K^{-1}

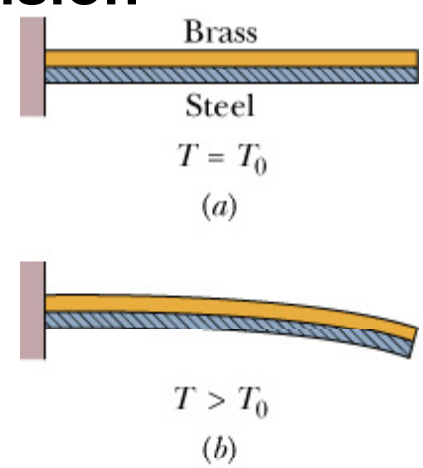
Some Molecular Speeds at Room Temperature (T = 300 K)[a]

Gas	Molar Mass (10^{-3} kg/mol)	v_{rms} (m/s)
Hydrogen (H_2)	2.02	1920
Helium (He)	4.0	1370
Water vapor (H_2O)	18.0	645
Nitrogen (N_2)	28.0	517
Oxygen (O_2)	32.0	483
Carbon dioxide (CO_2)	44.0	412
Sulfur dioxide (SO_2)	64.1	342

[a]For convenience, we often set room temperature = 300 K even though (at 27°C or 81°F) that represents a fairly warm room.

Linear thermal expansion





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

Some Coefficients of Linear Expansion[a]

Substance	α (10^{-6}/C°)	Substance	α (10^{-6}/C°)
Ice (at 0°C)	51	Steel	11
Lead	29	Glass (ordinary)	9
Aluminum	23	Glass (Pyrex)	3.2
Brass	19	Diamond	1.2
Copper	17	Invar[b]	0.7
Concrete	12	Fused quartz	0.5

[a]Room temperature values except for the listing for ice.

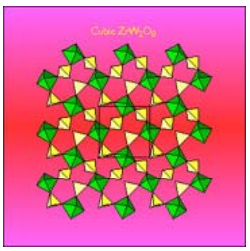
[b]This alloy was designed to have a low coefficient of expansion. The word is a shortened form of "invariable."

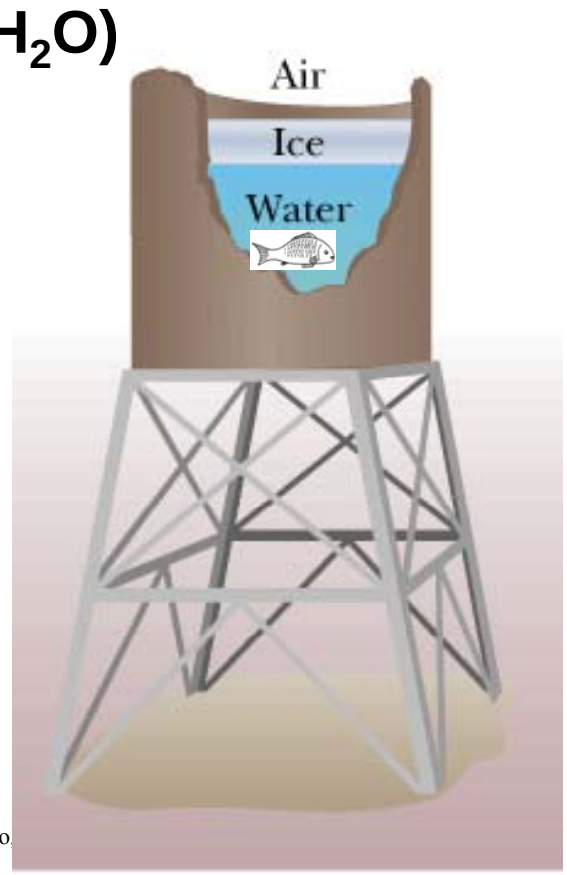
Properties of Water (H_2O)

negative thermal expansion of water between 0 and 4 C

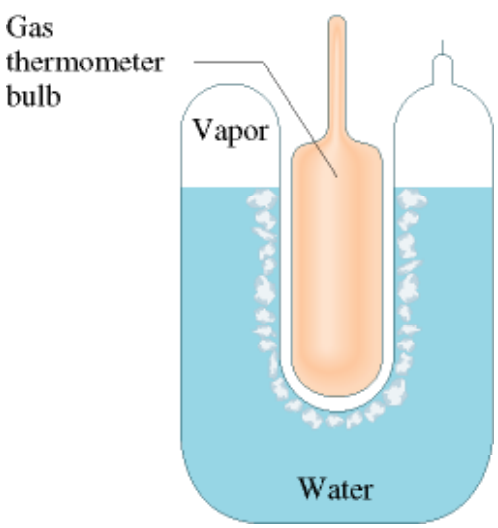
Freezes at 0 C, boils at 100 C

negative thermal expansion in ZrW_2O_8





The Triple Point of Water



A triple-point cell, in which solid ice, liquid water, and water vapor coexist in thermal equilibrium. By international agreement, the temperature of this mixture has been defined to be 273.16 K. The bulb of a constant-volume gas thermometer is shown inserted into the well of the cell.

Thermal expansion QZ

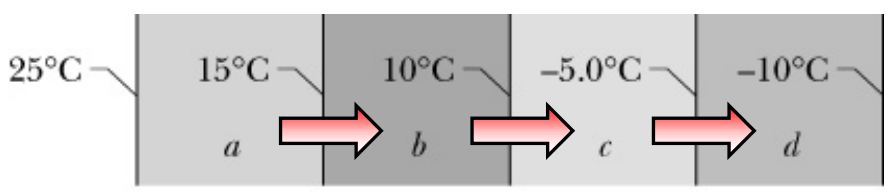
The coefficient of expansion of a certain steel is 0.000012 per C°. The coefficient of volume expansion, in $(C°)^{-1}$, is:

- **A.** $(0.000012)^3$
- **B.** $(4\pi/3)(0.000012)^3$
- **C.** 3×0.000012
- **D.** 0.000012
- **E.** depends on the shape of the volume to which it will be applied

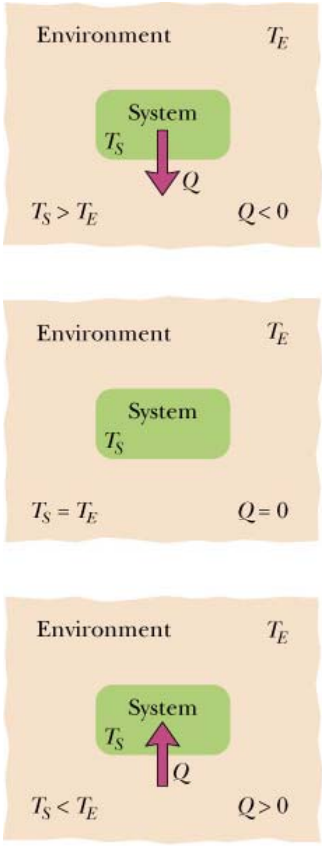
What is the ocean level increase due to +1 C° global warming ?
Water linear expansion coefficient is ~69e-6/C° at 20 C°.
Average ocean depth is 4 km

Heat : Temperature difference determines the Heat transfer process

What is the direction for the heat transfer Between a,b,c,d?



Heat and Heat Transfer



Heat is the energy that is transferred between a system and its environment because of a temperature difference that exists between them.

Units of Heat are Joules [J], same as for Work

If the temperature of a system exceeds that of its environment as in (*a*), heat Q is lost by the system to the environment until thermal equilibrium (*b*) is established. (*c*) If the temperature of the system is below that of the environment, heat is absorbed by the system until thermal equilibrium is established.

Heat Capacity

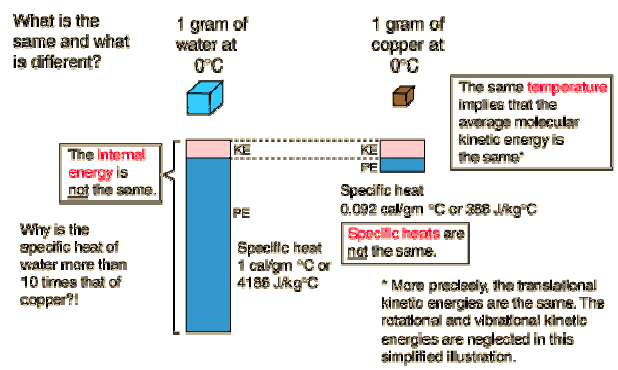
$$Q = C\,\Delta T = C(T_f - T_i)$$

Specific Heat

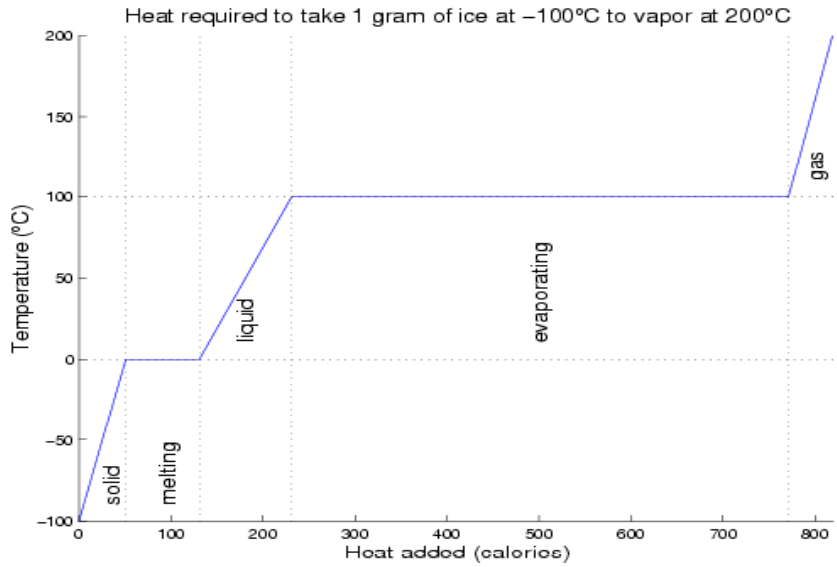
$$Q = cm\,\Delta T = cm(T_f - T_i)$$

Specific Heats of Some Substances at Room Temperature

Substance	Specific Heat cal/g·K	Specific Heat J/kg·K	Molar Specific Heat J/mol·K
Elemental Solids			
Lead	0.0305	128	26.5
Tungsten	0.0321	134	24.8
Silver	0.0564	236	25.5
Copper	0.0923	386	24.5
Aluminum	0.215	900	24.4
Other Solids			
Brass	0.092	380	
Granite	0.19	790	
Glass	0.20	840	
Ice (-10°C)	0.530	2220	
Liquids			
Mercury	0.033	140	
Ethyl alcohol	0.58	2430	
Seawater	0.93	3900	
Water	1.00	4190	



Properties of Water (H_2O)



Heat of Transformation

Heat absorbed by a material may change the material's physical state or phase—for example, from solid to liquid or from liquid to gas. The amount of energy required per unit mass to change the phase (but not the temperature) of a particular material is its **heat of transformation** L. Thus,

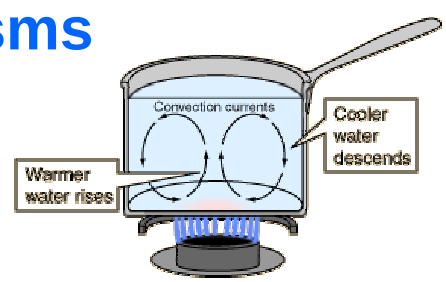
$$Q = Lm.$$

The **heat of vaporization** L_V is the amount of energy per unit mass that must be added to vaporize a liquid or that must be removed to condense a gas.

The **heat of fusion** L_F is the amount of energy per unit mass that must be added to melt a solid or that must be removed to freeze a liquid.

Heat Transfer Mechanisms

- **Convection**
- **Radiation**
- **Conduction**



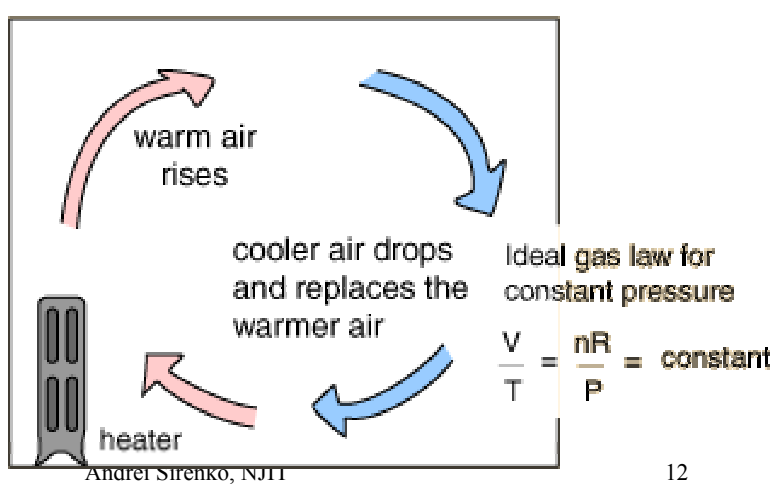
buoyant forces cause the warm air to rise

If volume increases, then density decreases, making it buoyant.

$$\uparrow \rho = \frac{m}{V} \uparrow$$

$$\uparrow \frac{V}{T} \uparrow = \text{constant}$$

If the temperature of a given mass of air increases, the volume must increase by the same factor.



Heat Transfer Mechanisms

- **Convection**
- **<u>Radiation</u>**
- **Conduction**

$$P = \frac{Q}{\Delta t}$$

$$P_{net} = P_{abs} - P_{rad} = \sigma \varepsilon A (T_{env}^4 - T^4).$$

σ= 5.6703 10^{-8} W/m^2·K^4 is called the *Stefan–Boltzmann constant*

ε represents the *emissivity* of the object's surface, which has a value between 0 and 1, depending on the composition of the surface. A surface with the maximum emissivity of 1.0 is said to be a *blackbody radiator,* but such a surface is an ideal limit and does not occur in nature.

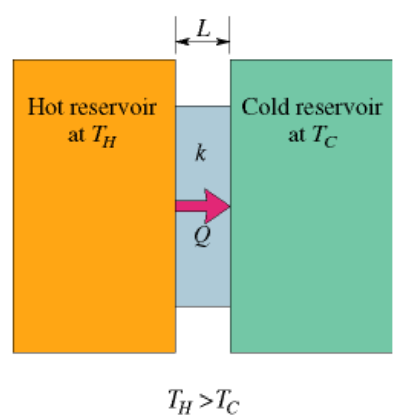
Heat Transfer Mechanisms

- **Convection**
- **Radiation**
- **Conduction**

Some Thermal Conductivities[a]

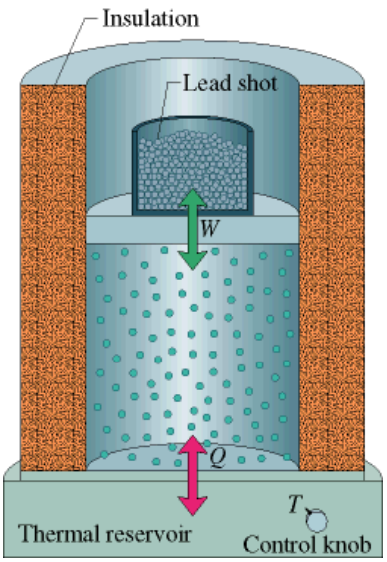
Substance	k (W/m·K)
Metals	
Stainless steel	14
Lead	35
Aluminum	235
Copper	401
Silver	428
Gases	
Air (dry)	0.026
Helium	0.15
Hydrogen	0.18
Building Materials	
Polyurethane form	0.024
Rock wool	0.043
Fiberglass	0.048
White pine	0.11
Window glass	1.0

[a]Conductivities change somewhat with temperature. The given values are at room temperature.



Q=kA(ΔT/L)t,
Where k is
the thermal conductivity

Heat and Work



A gas is confined to a cylinder with a movable piston. Heat Q can be added to, or withdrawn from, the gas by regulating the temperature T of the adjustable thermal reservoir. Work W can be done by the gas by raising or lowering the piston.

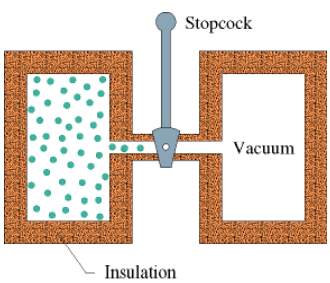
The First Law of Thermodynamics: Four Special Cases

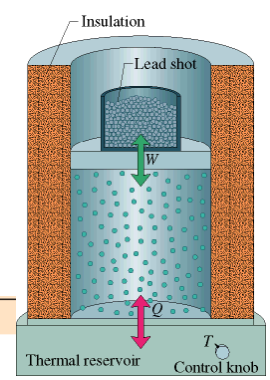
The Law: $\Delta E_{int} = Q - W$ (Eq. 19-26)

Process	Restriction	Consequence
Adiabatic	$Q = 0$	$\Delta E_{int} = -W$
Constant volume	$W = 0$	$\Delta E_{int} = Q$
Closed cycle	$\Delta E_{int} = 0$	$Q = W$
Free expansion	$Q = W = 0$	$\Delta E_{int} = 0$

The internal energy E_{int} of a system tends to increase if energy is added as heat Q and tends to decrease if energy is lost as work W done by the system.

Heat and Work





Some Special Cases of the First Law of Thermodynamics

2. ***Constant-volume processes.*** If the volume of a system (such as a gas) is held constant, that system can do no work. Putting $W = 0$ in the first law (Eq. 19-26) yields

$$\Delta E_{int} = Q \qquad \text{(constant – volume process).} \tag{19-29}$$

Thus, if heat is absorbed by a system (that is, if Q is positive), the internal energy of the system increases. Conversely, if heat is lost during the process (that is, if Q is negative), the internal energy of the system must decrease.

3. ***Cyclical processes.*** There are processes in which, after certain interchanges of heat and work, the system is restored to its initial state. In that case, no intrinsic property of the system—including its internal energy—can possibly change. Putting $\Delta E_{int} = 0$ in the first law (Eq. 19-26) yields

$$Q = W \qquad \text{(cyclical process).} \tag{19-30}$$

Thus, the net work done during the process must exactly equal the net amount of energy transferred as heat; the store of internal energy of the system remains unchanged. Cyclical processes form a closed loop on a p-V plot, as shown in Fig. 19-14f . We shall discuss such processes in some detail in Chapter 21 .

4. ***Free expansions.*** These are adiabatic processes in which no transfer of heat occurs between the system and its environment and no work is done on or by the system. Thus, $Q = W = 0$ and the first law requires that

$$\Delta E_{int} = 0 \qquad \text{(free expansion).} \tag{19-31}$$

Figure 19-16 shows how such an expansion can be carried out. A gas, which is in thermal equilibrium within itself, is initially confined by a closed stopcock to one half of an insulated double chamber; the other half is evacuated. The stopcock is opened, and the gas expands freely to fill both halves of the chamber. No heat is transferred to or from the gas because of the insulation. No work is done by the gas because it rushes into a vacuum and thus does not meet any pressure.

Review & Summary

Temperature; Thermometers

Temperature is an SI base quantity related to our sense of hot and cold. It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder.

Zeroth Law of Thermodynamics

When a thermometer and some other object are placed in contact with each other, they eventually reach thermal equilibrium. The reading of the thermometer is then taken to be the temperature of the other object. The process provides consistent and useful temperature measurements because of the **zeroth law of thermodynamics:** If bodies A and B are each in thermal equilibrium with a third body C (the thermometer), then A and B are in thermal equilibrium with each other.

The Kelvin Temperature Scale

In the SI system, temperature is measured on the **Kelvin scale,** which is based on the *triple point* of water (273.16 K). Other temperatures are then defined by use of a *constant-volume gas thermometer,* in which a sample of gas is maintained at constant volume so its pressure is proportional to its temperature. We define the *temperature* T as measured with a gas thermometer

Celsius and Fahrenheit Scales

The Celsius temperature scale is defined by

$$T_C = T - 273.15^\circ,$$

with T in kelvins. The Fahrenheit temperature scale is defined by

$$T_F = \tfrac{9}{5}T + 32^\circ.$$

Thermal Expansion

All objects change size with changes in temperature. For a temperature change ΔT, a change ΔL in any linear dimension L is given by

$$\Delta L = L\alpha\Delta T,$$

in which α is the **coefficient of linear expansion.** The change ΔV in the volume V of a solid or liquid is

$$\Delta V = V\beta\Delta T.$$

Here $\beta = 3\alpha$ is the material's **coefficient of volume expansion.**

Heat

Heat Q is energy that is transferred between a system and its environment because of a temperature difference between them. It can be measured in **joules** (J), **calories** (cal), **kilocalories** (Cal or kcal), or **British thermal units** (Btu), with

$$1 \text{ cal} = 3.969\times10^{-3} \text{ Btu} = 4.1860 \text{ J}.$$

Heat Capacity and Specific Heat

If heat Q is absorbed by an object, the object's temperature change $T_f - T_i$ is related to Q by

$$Q = C(T_f - T_i),$$

in which C is the **heat capacity** of the object. If the object has mass m, then

$$Q = cm(T_f - T_i),$$

where c is the **specific heat** of the material making up the object. The **molar specific heat** of a material is the heat capacity per mole, or per 6.02×10^{23} elementary units of the material.

Conduction, Convection, and Radiation

The rate P_{cond} at which energy is *conducted* through a slab whose faces are maintained at temperatures T_H and T_C is

$$P_{cond} = \frac{Q}{t} = kA\frac{T_H - T_C}{L},$$

in which A and L are the face area and length of the slab, and k is the thermal conductivity of the material.

Convection occurs when temperature differences cause an energy transfer by motion within a fluid. *Radiation* is an energy transfer via the emission of electromagnetic energy. The rate P_{rad} at which an object emits energy via thermal radiation is

$$P_{rad} = \sigma\varepsilon AT^4,$$

where σ (= 5.6703×10^{-8} W/m^2·K^4) is the Stefan–Boltzmann constant, ε is the emissivity of the object's surface, A is its surface area, and T is its surface temperature (in kelvins). The rate P_{abs} at which an object absorbs energy via thermal radiation from its environment, which is at the uniform temperature T_{env} (in kelvins), is

$$P_{abs} = \sigma\varepsilon AT_{env}^4.$$

Prepare for the First Common QZ

1. A cylindrical window of 18 cm radius in a submarine can withstand a maximum force of 5.0×10^5 N. What is the maximum depth in a lake to which the submarine can go without damaging the window? (ρ_w =1000 kg/m^3)
A) 501 m
B) 722 m
C) 1200 m
D) 1327 m
E) 1520 m

2. A solid object floats in water (density = 1000 kg/m^3) with three-fourth of its volume beneath the surface. What is the density of the object?

A) 1333 kg/m^3
B) 1000 kg/m^3
C) 750 kg/m^3
D) 250 kg/m^3
E) 120 kg/m^3

3. A weight of a solid object is 2.06 N when weighed in air and 1.76 N when weighed in a liquid of density 1200 kg/m^3. The density of the object is

A) 7000 kg/m^3
B) 3500 kg/m^3
C) 8240 kg/m^3
D) 14000 kg/m^3
E) 6500 kg/m^3