Physical Behavior of Matter

TOPIC 4

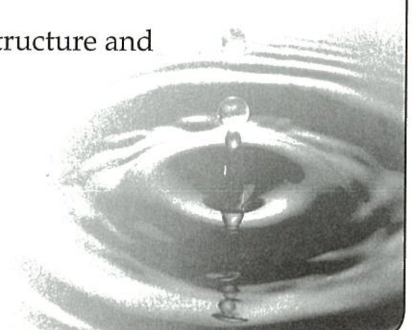
How Scientists Study Phases of Matter

Water, water everywhere. What makes it so unique?

The glaciers of the world hold quantities of solid water, which, if melted, would raise the oceans and change the face of the continents. Vast quantities of gaseous water—water vapor—swirl around our heads, produced by the evaporation of liquid water and sublimation of solid water. Water vapor condenses and falls as rain. Liquid water is, well, everywhere.

So why is water so unique? It's a combination of structure and bonding that gives H_2O its unusual properties.

Learn more about phases of matter in this topic.



TOPIC 4 Physical Behavior of Matter

Vocabulary

condensation	heat	solid phase
deposition	heat of fusion	sublimation
freezing	heat of vaporization	temperature
fusion	kinetic molecular theory	vaporization
gaseous phase	liquid phase	

Digging Deeper

Glass is a common substance that appears to be a solid. However, careful analysis shows that glass does not have a true crystalline structure and is not a true solid. Over time, the particles making up glass are able to slowly flow past one another. Substances like glass are called supercooled liquids.

There is a fourth phase of matter, plasma. A plasma is a gas or vapor in which some or all of the electrons have been removed from the atoms.

Topic Overview

In this chapter you will first examine the solid, liquid, and gaseous phases of matter. Next, you will study how to calculate the heat exchanged during heating, cooling, and phase changes. The kinetic molecular theory will then be presented to explain the behavior of gases. Finally, you'll learn about the various means of separating mixtures.

Phases of Matter

An element, compound or mixture may exist in the form of a solid, liquid, or a gas. These three forms are called the phases of matter.

The **solid phase** contains matter that is held in a rigid form. Because of this rigid form, a substance in the solid phase has a definite volume and shape. Strong attractive forces among the particles in a solid hold the particles in fixed locations. True solids have a crystalline structure.

Particles in the **liquid phase** are not held together as rigidly as those in the solid phase. Liquid phase particles are able to move past one another. The mobility of the particles prevents liquids from having a definite shape. The particles, however, are held together with sufficient attractive force to give a liquid a definite volume.

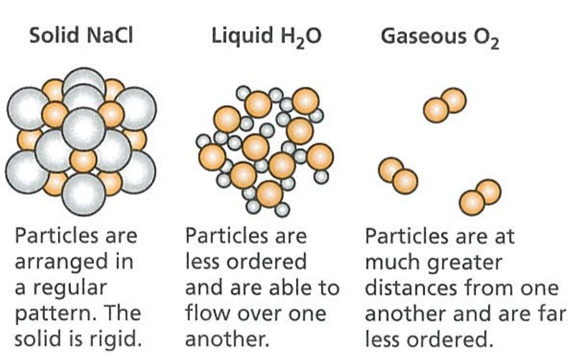


Figure 4-1. Particles of matter in three phases

Particles in the **gaseous phase** have minimal attractive forces holding them together. Due to this lack of attraction among particles, gases have neither a definite shape nor a definite volume. Gases spread out indefinitely unless they are confined in a container. In a closed container, the gaseous particles always expand to fill the volume of the container. A vapor is the gaseous phase of a substance that is a liquid or a solid at normal conditions. Figure 4-1 summarizes the three phases of matter.

Heating and Cooling Curves

Figure 4-2 shows the heating of a hypothetical substance from the solid phase to the gaseous phase. At time = 0, shown as point A on the graph, the temperature of the solid is 10°C. Heat is then added to the substance at a constant rate. From time = 0 to time = 2 minutes, the temperature rises at a constant rate until the temperature of the solid reaches its melting point (B). During this portion of the process (AB), the kinetic energy of the substance is increasing.

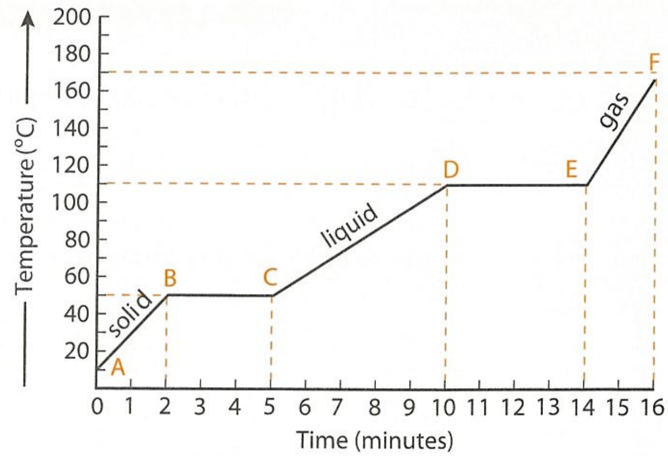


Figure 4-2. A typical heating curve: The heating of a solid (AB), liquid (CD), and gas (EF) results in an increase in the substance's temperature. Phase changes that occur during melting (BC) and boiling (DE) are not accompanied by temperature changes.

Eventually some of the particles in the substance possess enough kinetic energy to break the bonds holding them in the solid phase; melting, also known as **fusion,** begins (B). During the melting process (BC), the temperature remains constant even though heat is still being added at a constant rate. During this time, the heat is absorbed by the substance in the form of potential energy. Both solid and liquid phases of the substance are present during the melting process. As time goes on, the amount of liquid continually increases and the amount of solid continually decreases. Because the liquid phase of a substance has more potential energy than the solid phase, the potential energy of the substance increases during the melting process. The unchanging temperature during melting is evidence of the fact that the substance's kinetic energy remains constant during the process. The amount of heat needed to convert a solid at its melting point to a liquid is called the heat of fusion.

When all of the solid has melted (C) and only the liquid phase is present, the temperature once again begins to rise. This temperature rise is due to the increase in kinetic energy of the substance. The temperature continues to rise until the boiling point is reached (D). Boiling, also known as **vaporization,** begins as some of the particles in the liquid have enough kinetic energy to break free from the attractive forces holding them in the liquid phase. These particles escape the liquid and enter the gas phase. Once boiling begins, the temperature remains constant as the substance's potential energy increases. During this phase change, both the liquid and gaseous (vapor) phases are present. Because the gaseous phase of a substance has more potential energy than the liquid phase, the potential energy of the substance increases as heat is absorbed during the boiling process. If heat is added to the substance in its gas phase, the temperature of the gas begins to rise (EF).

Heating Curve Summary All of the steps (AB, BC, CD, DE, and EF) shown in Figure 4-2 are endothermic.

AB: heating of a solid, one phase present, kinetic energy increases
BC: melting of a solid, two phases present, potential energy increases, kinetic energy remains constant
CD: heating of a liquid, one phase present, kinetic energy increases
DE: boiling of a liquid, two phases present, potential energy increases, kinetic energy remains constant
EF: heating of a gas, one phase present, kinetic energy increases

Memory Jogger

Endothermic reactions absorb heat energy (heat is a reactant). Exothermic reactions release heat energy (heat is a product).

Cooling Curve Summary If a gas at high temperature is allowed to cool at a constant rate, a cooling curve results. See Figure 4-3. Note that the reverse of boiling is called **condensation,** and the reverse of melting is called **freezing.** Freezing is also called solidification. All of the steps shown in Figure 4-3 are exothermic.

AB: cooling of a gas (vapor), one phase present, kinetic energy decreases
BC: condensation of the gas (vapor) to liquid, two phases present, potential energy decreases, kinetic energy remains constant
CD: cooling of a liquid, one phase present, kinetic energy decreases
DE: solidification (freezing) of a liquid, two phases present, potential energy decreases, kinetic energy remains the same
EF: cooling of a solid, one phase present, kinetic energy decreases

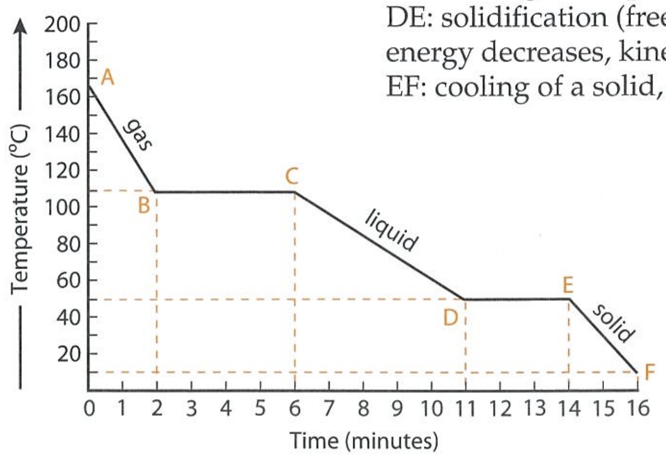


Figure 4-3. A typical cooling curve: The cooling of a gas (AB), liquid (CD), and solid (EF) results in a decrease in the substance's temperature. Phase changes occurring during condensation (BC) and freezing (DE) are not accompanied by temperature changes.

Sublimation and Deposition

Heating and cooling curves show the normal transitions between phases. Some substances, however, change directly from a solid to a gas without passing through a noticeable liquid phase. An example is solid carbon dioxide (CO_2), which changes from a solid to a gas at normal atmospheric pressure. This process, in which a solid changes directly into a gas, is called **sublimation.** A substance that undergoes sublimation is said to sublime. The reverse of the sublimation process, in which a gas changes directly into a solid, is called **deposition.**

Review Questions — Set 4.1

1. Which substance has a definite shape and a definite volume at STP?

(1) $NaCl(aq)$ (3) $CCl_4(\ell)$
(2) $Cl_2(g)$ (4) $AlCl_3(s)$

2. At STP, which element has a definite shape and volume?

(1) Ag (2) Hg (3) Ne (4) Xe

3. Which sample is most likely to take the shape of and occupy the total volume of its container?

(1) $CO_2(g)$
(2) $CO_2(\ell)$
(3) $CO_2(aq)$
(4) $CO_2(s)$

4. As a substance changes from a liquid to a gas, the average distance between molecules

(1) decreases
(2) increases
(3) remains the same

5. Which substance takes the shape of and fills the volume of any container into which it is placed?

(1) $H_2O(\ell)$ (3) $I_2(s)$
(2) $CO_2(g)$ (4) $Hg(\ell)$

6. Which sample of matter sublimes at room temperature and standard pressure?

(1) $Br_2(\ell)$ (3) $CO_2(s)$
(2) $Cl_2(g)$ (4) $SO_2(aq)$

7. Which phase change represents sublimation?

(1) $H_2O(\ell) \rightarrow H_2O(s)$ (3) $I_2(s) \rightarrow I_2(g)$
(2) $H_2O(\ell) \rightarrow H_2O(g)$ (4) $I_2(s) \rightarrow I_2(\ell)$

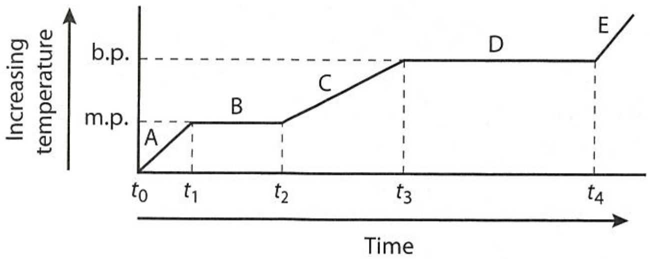
8. Which phase change represents sublimation?

(1) $NH_3(\ell) \rightarrow NH_3(g)$ (3) $KI(s) \rightarrow KI(\ell)$
(2) $CO_2(s) \rightarrow CO_2(g)$ (4) $H_2O(\ell) \rightarrow H_2O(s)$

9. As ice cools from 273 K to 263 K, the average kinetic energy of its molecules

(1) decreases
(2) increases
(3) remains the same

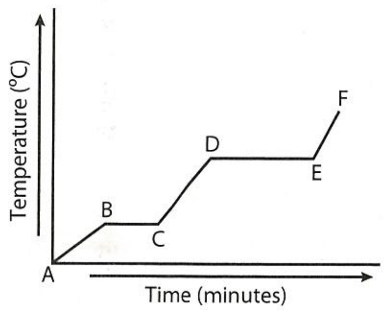
10. A solid substance initially at a temperature below its melting point is heated at a constant rate. The heating curve for the substance is shown in the graph below.



Which portions of the graph represent times when heat is absorbed and potential energy increases while kinetic energy remains constant?

(1) A and B
(2) B and D
(3) A and C
(4) C and D

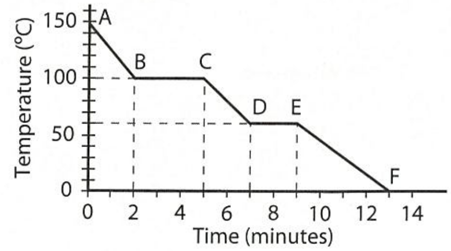
11. A solid substance initially at a temperature below its melting point is heated at a constant rate. The heating curve for the substance is shown in the graph below.



Which segment of the graph represents a time when both the solid and liquid phases are present?

(1) AB (2) BC (3) DE (4) EF

12. A gaseous substance initially at a temperature above its boiling point is cooled at a constant rate. The cooling curve for the substance is shown below.



How much time passes between the first appearance of the liquid phase of the substance and the presence of the substance completely in its solid phase?

(1) 5 minutes
(2) 2 minutes
(3) 7 minutes
(4) 4 minutes

13. The heat of fusion is defined as the energy required (at constant temperature) to change a

(1) gas to a liquid
(2) gas to a solid
(3) solid to a gas
(4) solid to a liquid

14. During which process is potential energy decreasing and average kinetic energy remaining the same?

(1) A liquid is converted to a solid at its freezing point.
(2) A solid is converted to a liquid at its melting point.
(3) A gas is cooled from a temperature of 120°C to 115°C.
(4) A liquid is heated from 38°C to 58°C.

15. Which phase change is endothermic?

(1) gas → solid
(2) gas → liquid
(3) liquid → solid
(4) liquid → gas

16. Which phase change is exothermic?

(1) $H_2O(s) \rightarrow H_2O(\ell)$
(2) $H_2O(\ell) \rightarrow H_2O(s)$
(3) $H_2O(s) \rightarrow H_2O(g)$
(4) $H_2O(\ell) \rightarrow H_2O(g)$

Temperature Scales

The **temperature** of a substance is a measure of the average kinetic energy of its particles. The particles of all substances at the same temperature have the same average kinetic energy. The temperature difference between two bodies indicates the direction of heat flow. That is, whenever two objects with different temperatures are in contact, heat flows from the object at the higher temperature to the object at the lower temperature. The heat flow continues until the two objects are at the same temperature.

The average kinetic energy depends only on the temperature of the substance, and not on the nature or amount of the material. Thus, 10 g of H_2O at 50°C has greater average kinetic energy than 500 g of Fe(*s*) at 20°C.

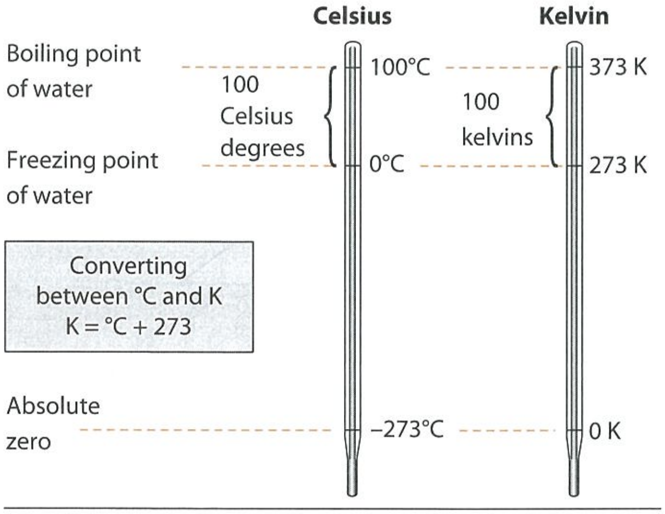


Figure 4-4. Comparison of Celsius and Kelvin temperature scales

Temperature is measured using a thermometer. Thermometers are calibrated by establishing two fixed reference points; the distance between them is then divided into the desired number of units. The fixed points on common thermometers are the freezing and boiling points of water. The freezing point of water is the ice–water (solid–liquid) equilibrium temperature at normal atmospheric pressure (101.3 kPa). The boiling point of water is the water–steam (liquid–gas) equilibrium temperature at normal atmospheric pressure. As shown in Figure 4-4, the boiling and freezing reference points are used on both the Celsius and Kelvin temperature scales. Note that there are 100 units between the two reference points on both the Celsius and Kelvin scales.

Because there are an equal number of divisions between the fixed reference points of both the Celsius and Kelvin scales, a change of one degree Celsius is equal to a change of one Kelvin. A change of 50°C represents the same temperature change as 50 Kelvins. The Celsius and Kelvin scales are related by the following equation:

$$K = °C + 273$$

Although often confused, heat and temperature are not the same. **Heat** is a measure of the amount of energy transferred from one substance to another. Heat is measured in units of calories or joules. Temperature is a measure of the average kinetic energy of a substance's particles, and is measured in degrees Celsius or in Kelvins. An example of the difference between heat and temperature involves the melting of ice. It requires more energy to melt 10 g of ice than it does to melt 1 g of ice, yet in both cases the temperature of the ice does not change.

SAMPLE PROBLEM

What Kelvin temperature is equivalent to 35°C?

SOLUTION: Identify the known and unknown values.

Known	*Unknown*
temperature = 35°C	temperature = ? K

Substitute the known temperature into the equation relating Kelvin and Celsius, and solve.

K = °C + 273
K = 35 + 273
K = 308

308 K is equivalent to 35°C.

Review Questions

Set 4.2

17. Which is not a form of energy?
(1) light (3) electricity
(2) temperature (4) heat

18. Which unit is used to express the amount of energy absorbed or released during a chemical reaction?
(1) degree (3) gram
(2) torr (4) joule

19. Which term represents a form of energy?
(1) heat (3) kilojoule
(2) degree (4) temperature

20. The minimum number of fixed reference points required to establish the Celsius temperature scale for a thermometer is
(1) 1 (2) 2 (3) 3 (4) 4

21. What are the fixed reference points on the Celsius thermometer?
(1) 32 and 100 (3) 32 and 212
(2) 0 and 212 (4) 0 and 100

22. The difference between the boiling point and the freezing point of pure water at standard pressure is
(1) 32 K (2) 273 K (3) 100 K (4) 373 K

23. What is the freezing point of water on the Kelvin scale at standard pressure?
(1) 0 K (2) 32 K (3) 100 K (4) 273 K

24. When the temperature of an object changes by 100°C, the same temperature change in Kelvins would be
(1) 100 K (2) 173 K (3) 273 K (4) 373 K

25. Energy is added to a substance. Compared to the Celsius temperature of the substance, the Kelvin temperature
(1) will always be 273 greater
(2) will always be 273 lower
(3) will have the same reading at 0
(4) will have the same reading at 273

26. What Kelvin temperature is equal to −73°C?
(1) 100 K (2) 173 K (3) 200 K (4) 346 K

27. Which temperature is equal to 20 K?
(1) −253°C (2) −293°C (3) 253°C (4) 293°C

28. Compared to a 26-gram sample of Cu(*s*) at STP, the atoms of a 52-gram sample of Fe(*s*) have
(1) a higher average kinetic energy
(2) a lower average kinetic energy
(3) the same average kinetic energy
(4) twice as much average kinetic energy

29. The average kinetic energy of water molecules increases when
(1) $H_2O(s)$ changes to $H_2O(\ell)$ at 0°C
(2) $H_2O(\ell)$ changes to $H_2O(s)$ at 0°C
(3) $H_2O(\ell)$ at 10°C changes to $H_2O(\ell)$ at 20°C
(4) $H_2O(\ell)$ at 20°C changes to $H_2O(s)$ at 10°C

Measurement of Heat Energy

The amount of heat given off or absorbed in a reaction can be calculated using the following equation:

$$q = mC\Delta T$$

q = heat (in joules)
m = mass of the substance
C = specific heat capacity of substance
$\Delta T = (\text{Temperature}_{\text{initial}} - \text{Temperature}_{\text{final}})$

SAMPLE PROBLEM

How many joules are absorbed when 50.0 g of water are heated from 30.2°C to 58.6°C?

SOLUTION: Identify the known and unknown values.

Known
$m = 50.0$ g
$C_{water} = 4.18$ J/g•°C
$\Delta T = (58.6°C - 30.2°C) = 28.4°C$

Unknown
$q = ?$ J

Substitute the known values into the formula $q = mC\Delta T$ and solve for q.

$q = (50.0\ \cancel{g})(4.18\ \text{J}/\cancel{g}\bullet\cancel{°C})(28.4\cancel{°C})$
$q = 5936\ \text{J} = 5.94 \times 10^3\ \text{J}$

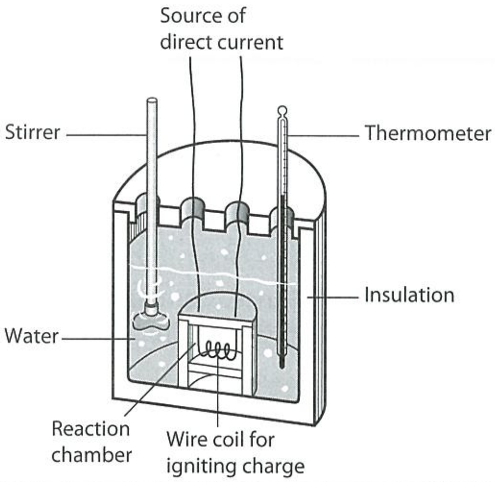


Figure 4-5. Cutaway drawing showing the components of a calorimeter

As shown in Figure 4-5, a device known as a calorimeter can be used to measure the amount of heat given off in a reaction. The reaction takes place in the reaction chamber, and the heat released by the reaction is absorbed by the surrounding water. By measuring the temperature increase of the water, the heat given off in the reaction can be calculated.

Whenever a substance undergoes a temperature change, the equation $q = mc\Delta T$ can be used to calculate the heat involved. However, this equation cannot be used to determine the amount of heat required to melt or boil a substance. Why? Temperature remains constant during a phase change, so there is no ΔT, and the equation cannot be used. Recall from Figure 4-2 that the line segment BC represents the melting of a substance. To determine the heat required for a phase change such as this, you must use an equation involving the substance's heat of fusion.

Heat of Fusion

The amount of heat needed to convert a unit mass of a substance from solid to liquid at its melting point is called the **heat of fusion.** The heat of fusion of solid water (ice) at 0°C and 1 atmosphere is 334 J/g. The heat absorbed by the substance during the melting process increases the potential energy of the substance without increasing the average kinetic energy of the substance's particles. Because there is no change in kinetic energy, there is no temperature change during the process.

SAMPLE PROBLEM

How many joules are required to melt 255 g of ice at 0°C?

SOLUTION: Identify the known and unknown values.

Known	*Unknown*
$m = 255$ g	$q = ?$ J
heat of fusion = 334 J/g	

Multiply the heat of fusion by the total mass of ice to determine the heat required.

$q = (255 \not{g})(334\ J/\not{g}) = 85{,}170\ J = 85.2\ kJ$

The process of melting is an endothermic process, that is, it requires heat. Therefore, the reverse process of freezing (also called solidification) must be exothermic. During the freezing process, water releases 334 J/g of heat and its potential energy decreases.

Heat of Vaporization

During the boiling process, a substance in the liquid phase is converted to the gaseous (vapor) phase. The temperature remains constant during the boiling process even though energy is constantly added. The heat energy increases the potential energy of the particles in the gaseous phase. The amount of heat needed to convert a unit mass of a substance from its liquid phase to its vapor phase at constant temperature is called its **heat of vaporization.** As heat is added, the particles absorb sufficient energy to overcome the attractive forces holding them in the liquid phase. The potential energy of the system increases as the temperature remains constant. The heat of vaporization of water at 100°C and 1 atmosphere is 2260 J/g.

The condensation process is the reverse of boiling process. Therefore the heat of condensation is also 2260 J/g. Condensation is an exothermic process.

SAMPLE PROBLEM

How many joules of energy are required to vaporize 423 g of water at 100°C and 1 atm?

SOLUTION: Identify the known and unknown values.

Known	Unknown
$m = 423$ g	$q = ?$ J
heat of fusion = 2260 J/g	

Multiply the heat of vaporization by the total mass of water to determine the heat required.

$q = (423\ \cancel{g})(2260\ J/\cancel{g}) = 955{,}980\ J = 956\ kJ$

Review Questions — Set 4.3

30. When 25.0 grams of water are cooled from 20.0°C to 10.0°C, the number of joules of heat energy released is

(1) 42 (3) 840
(2) 105 (4) 1050

31. How many joules of heat energy are released when 50.0 g of water are cooled from 70.0°C to 60.0°C?

(1) 41.8 J (3) 209 J
(2) 2.09×10^3 J (4) 4.18×10^3 J

32. What is the total number of joules of heat energy absorbed when the temperature of 200.0 g of water is raised from 10.0°C to 40.0°C?

(1) 126 J (3) 2.51×10^4 J
(2) 840. J (4) 3.36×10^4 J

33. How many kilojoules of heat energy are absorbed when 100.0 g of water are heated from 20.0°C to 30.0°C?

(1) 4.18 kJ (3) 418 kJ
(2) 41.8 kJ (4) 0.418 kJ

34. The temperature of a sample of water in the liquid phase is raised 30.0°C by the addition of 3762 J. What is the mass of the water?

(1) 0.03 g (3) 30.0 g
(2) 0.30 g (4) 300.0 g

35. When 418. joules of heat energy are added to 10.0 grams of water at 20.0°C, the final temperature of the water will be

(1) 10.0°C (3) 40.0°C
(2) 30.0°C (4) 100.0°C

36. When 20.0 g of a substance are completely melted at its melting point, 3444 J are absorbed. What is the heat of fusion of this substance?

(1) 41 J/g (3) 16,400 J/g
(2) 172 J/g (4) 68,900 J/g

37. The heat of vaporization of a liquid is 1344 J/g. What is the minimum number of joules needed to change 40.0 g of the liquid to vapor at the boiling point?

(1) 33.6 J (3) 13,776 J
(2) 1344 J (4) 53,800 J

For each of the following problems, be sure to show your work, use the proper units, and express your answer to the correct number of significant figures.

38. A sample of water is heated from 10.0°C to 15.0°C by the addition of 125 J of heat. What is the mass of the water?

39. What is the total number of joules absorbed by 65.0 g of water when the temperature of the water is raised from 25.0°C to 40.0°C?

40. If 100.0 J are added to 20.0 g of water at 30.0°C, what will be the final temperature of the water?

41. The temperature of 50.0 g of water was raised to 50.0°C by the addition of 1.0 kJ of heat energy. What was the initial temperature of the water?

42. What would be the temperature change if 3.0 g of water absorbed 15 J of heat?

43. What is the total number of kilojoules of heat needed to change 150. g of ice to water at 0°C?

44. What is the total number of kilojoules required to completely boil 100.0 g of water at 100.0°C and 1 atmosphere?

45. How much energy is required to vaporize 10.00 g of water at its boiling point?

46. At 1 atmosphere of pressure, 25.0 g of a compound at its normal boiling point are converted to a gas by the addition of 34,400 J. What is the heat of vaporization for this compound in J/g?

Behavior of Gases

Scientists construct models to explain the behavior of substances. While the gas laws describe how gases behave, they do not explain why gases behave the way they do. The **kinetic molecular theory** (KMT) is a model or theory that is used to explain the behavior of gases. This theory describes the relationships among pressure, volume, temperature, velocity, frequency, and force of collisions.

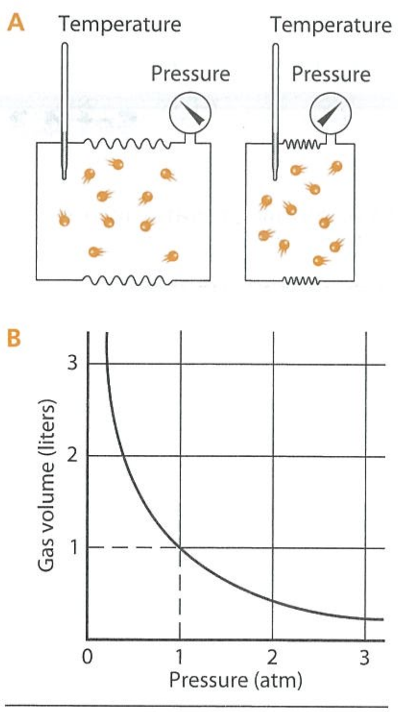


Figure 4-6. Pressure-volume relationship: (A) At constant temperature, as the volume of a gas decreases, the pressure it exerts increases. (B) This graph shows the variation of gas volume with changing pressure at constant temperature. *PV* = constant

Kinetic Molecular Theory

The major ideas of kinetic molecular theory are summarized in the following statements:

- Gases contain particles (usually molecules or atoms) that are in constant, random, straight-line motion.
- Gas particles collide with each other and with the walls of the container. These collisions may result in a transfer of energy among the particles, but there is no net loss of energy as the result of these collisions. The collisions are said to be perfectly elastic.
- Gas particles are separated by relatively great distances. Because of this, the volume occupied by the particles themselves is negligible and need not be accounted for.
- Gas particles do not attract each other.

Relationship of Pressure and Numbers of Gas Particles The kinetic molecular theory easily explains why gases exert pressure. Not only do gas molecules collide with each other, but they also collide with the walls of their container. These collisions with the container wall exert a force over the surface area of the wall—the particles exert pressure on the wall. For example, if you add more air to a bicycle tire, the pressure is increased. The greater the number of air particles, the greater the pressure. Pressure and the number of gas molecules are directly proportional.

Relationship of Pressure and Volume of a Gas Picture a cylinder with a piston at one end. If the piston can be pushed in, the volume will decrease. The molecules of the gas become more concentrated and hit the walls of the container more often. The pressure increases. If the piston is moved outward so as to increase the volume, the molecules hit the walls less often, causing a decrease in pressure. Thus volume and pressure are indirectly, or inversely, related. If one of the variables (volume or pressure) increases, the other must decrease.

Relationship of Temperature and Pressure of a Gas You may recall that the temperature of a substance is defined as a measure of the average kinetic energy of its particles. The kinetic energy (KE) is given by the formula $KE = (\frac{1}{2})mv^2$. As the temperature rises, the kinetic energy increases. This increase is due not to an increase in the mass of the particles, but rather to an increase in their velocity. As the temperature rises, the velocity of the particles increases, causing them to hit the walls of the container more often and with greater force. Thus an increase in temperature causes the pressure to increase. Pressure and temperature are directly related.

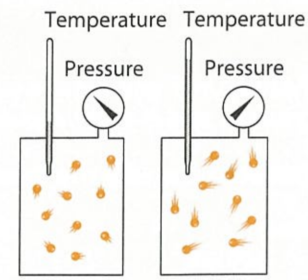


Figure 4-7. Temperature-pressure relationship: At constant volume, as the temperature of a gas increases, the pressure it exerts increases.

Relationship of Temperature and Volume of a Gas If the volume of a container could change while the pressure remained constant, how would volume and temperature be related? As the temperature increases, the molecules push harder on the piston of the container. When the internal pressure of the container exceeds the pressure pushing from the outside, the piston is pushed upward and the volume increases. The piston continues to move until the internal and external pressures are equal. Thus volume and temperature are directly related.

Relationship of Temperature and Velocity You know that as the temperature of a substance increases, its kinetic energy increases. What is the cause of this increase in temperature? Obviously, the masses of the particles do not increase; therefore, it must be the velocity of the particles that increases. The higher the temperature, the greater the average velocity of the particles.

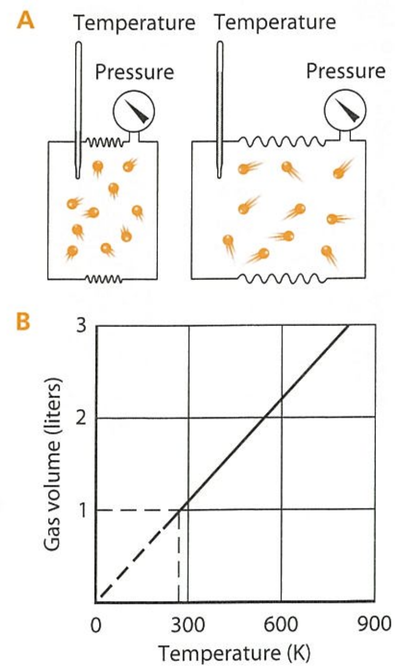


Figure 4-8. Temperature-volume relationship: (A) At constant pressure, as the temperature of a gas increases, the volume it occupies increases. (B) This graph shows the variation of gas volume with changing Kelvin temperature at constant pressure. V/T = a constant

Combined Gas Law Equation The relationships among pressure, temperature, and volume can be mathematically represented by an equation known as the combined gas law.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

This law can be used to solve problems involving the gas properties of temperature (T, which must be in Kelvins to avoid introducing negative values), volume (V), and pressure (P) whenever two or more of these properties are involved. For problems in which two of the properties are involved and the third property remains constant, simply cancel out the variable representing the constant property and then solve for the remaining unknown.

SAMPLE PROBLEM

What volume will a gas occupy if the pressure on 244 cm^3 gas at 4.0 atm is increased to 6.0 atm? Assume the temperature remains constant.

SOLUTION: Identify the known and unknown values.

Known
$V_1 = 244\ cm^3$
$P_1 = 4.0\ atm$
$P_2 = 6.0\ atm$
T = constant

Unknown
$V_2 = ?\ cm^3$

1. Since temperature remains constant, delete the T variable from the combined gas law equation.

$$\frac{P_1V_1}{\cancel{T_1}} = \frac{P_2V_2}{\cancel{T_2}} \quad \text{yields} \quad P_1V_1 = P_2V_2$$

2. Rearrange the equation to solve for V_2.

$$V_2 = (P_1V_1)/P_2$$

3. Substitute the known values and solve.

$$V_2 = (244\ cm^3)(4.0\ \cancel{atm})/(6.0\ \cancel{atm}) = 160\ cm^3$$

SAMPLE PROBLEM

If 75 cm^3 of a gas is at STP, what volume will the gas occupy if the temperature is raised to 75°C and the pressure is increased to 945 torr?

SOLUTION: Identify the known and unknown values:

Known
$P_1 = 760\ torr$
$V_1 = 75\ cm^3$
$T_1 = 0°C$
$P_2 = 945\ torr$
$T_2 = 75°C$

Unknown
$V_2 = ?\ cm^3$

1. Convert the known temperatures into Kelvin.

$$T_1 = 0 + 273 = 273\ K$$
$$T_2 = 75 + 273 = 348\ K$$

2. Solve the combined gas law equation for V_2.

$$V_2 = \frac{P_1V_1T_2}{P_2T_1}$$

3. Substitute the known values and solve for V_2.

$$V_2 = \frac{(760\ \cancel{torr})(75\ cm^3)(348\ \cancel{K})}{(945\ \cancel{torr})(273\ \cancel{K})}$$

$$V_2 = 77\ cm^3$$

Ideal Versus Real Gases

Kinetic molecular theory explains the behavior of gases by using a model gas called an "ideal" gas. When the gas laws are used to solve problems involving "real" gases, the answers obtained often do not exactly match the results obtained in the lab. This is because the ideal gas model does not exactly match the behavior of real gases. These discrepancies arise from the fact that two of the assumptions made by kinetic molecular theory are not exactly correct.

- **Gas particles do not attract one another.** In most cases, the attractive forces between gas particles are so small that they can be disregarded. However, when conditions become extreme, these small forces become important. For example, water molecules in the atmosphere attract each other when temperatures become cold enough. The water molecules combine to form snow or rain.

- **Gas particles do not occupy volume.** Although gas particles themselves occupy a small volume of space under normal conditions, as pressure increases the volume occupied by the particles can no longer be ignored. At high pressures, the increased concentration of particles leads to more frequent collisions and far greater chances of combining.

A gas is said to be "ideal" if it behaves exactly as predicted. Although no gas is truly "ideal," hydrogen and helium are nearly ideal in behavior. In general, gases vary from ideal behavior because of two factors: increasing mass and increasing polarity. These factors become important as pressure is increased and temperature is decreased. Gases are most ideal at low pressures and high temperatures.

Memory Jogger

Standard temperature and pressure (STP) is defined as one atmosphere of pressure and a temperature of 0°C (273 K).

Pressure is defined as force per unit area. In chemistry, pressure is often expressed in units of torr, millimeters of mercury (mm Hg), atmospheres (atm), and kilopascals (kPa). Normal atmospheric pressure is 760 torr, 760 mm Hg, 1 atm, and 101.3 kPa.

Avogadro's Hypothesis

Avogadro proposed a rather startling theory about equal volumes of gases. He stated that when the volume, temperature, and pressure of two gases were the same, they contained the same number of molecules. Thus, 12 liters of nitrogen at STP would contain the same number of molecules as 12 liters of oxygen at STP, or for that matter, the same number of molecules as any gas at those conditions. Today, we believe that 22.4 liters of any gas at STP contains one mole of the gas. For example, 22.4 liters of neon contains one mole of neon—10g. One mole of any substance contains 6.02×10^{23} molecules, a number called Avogadro's number.

Review Questions — Set 4.4

47. What volume will a 300.0 mL sample of a gas at STP occupy when the pressure is doubled at constant temperature?

(1) 150.0 mL
(2) 600.0 mL
(3) 2000. mL
(4) 4000. mL

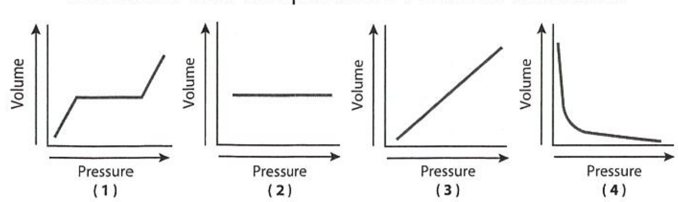
48. The volume of a sample of a gas at 273°C is 200.0 L. If the volume is decreased to 100.0 L at constant pressure, what will be the new temperature of the gas?

(1) 0 K (2) 100 K (3) 273 K (4) 546 K

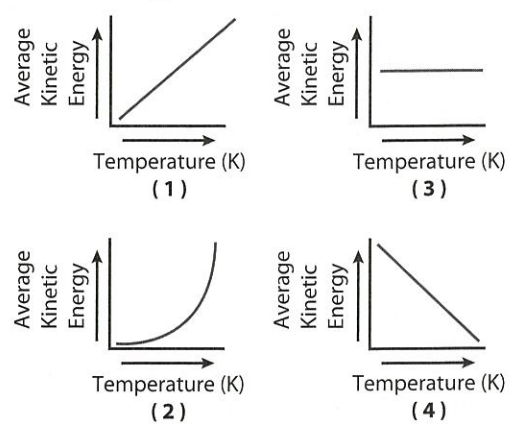
49. At constant pressure, how does the volume of 1 mole of an ideal gas vary?

(1) directly with the Kelvin temperature
(2) indirectly with the Kelvin temperature
(3) directly with the mass of the gas
(4) indirectly with the mass of the gas

50. Which graph best shows the change in the volume of 1 mole of nitrogen gas as pressure increases and temperature remains constant?



51. Which graph best shows the relationship between Kelvin temperature and average kinetic energy?



52. Under which conditions will the volume of a given sample of a gas always decrease?

(1) decreased pressure and decreased temperature
(2) decreased pressure and increased temperature
(3) increased pressure and decreased temperature
(4) increased pressure and increased temperature

53. At constant temperature, the relationship between the volume (V) of a gas and its pressure (P) is

(1) V = (constant)P
(2) P = (constant)V
(3) PV = constant
(4) V/P = constant

54. Which changes in pressure and temperature occur as a given mass of gas at 0.5 atm and 546 K is changed to STP?

(1) The pressure is doubled and the temperature is halved.
(2) The pressure is doubled and the temperature is doubled.
(3) The pressure is halved and the temperature is halved.
(4) The pressure is halved and the temperature is doubled.

55. As the temperature of a gas is increased from 0°C to 10°C at constant pressure, the volume of the gas

(1) increases by $\frac{1}{273}$
(2) increases by $\frac{10}{273}$
(3) decreases by $\frac{1}{273}$
(4) decreases by $\frac{10}{273}$

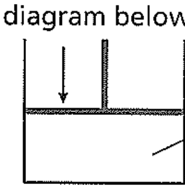
56. The table below shows the changes in the volume of a gas as the pressure changes at constant temperature.

Pressure (atm)	Volume (mL)
0.5	1000
1.0	500
2.0	250

Which equation best expresses the relationship between pressure and volume for the gas?

(1) $\frac{P}{V}$ = 500 atm•mL
(2) PV = 500 atm•mL
(3) $\frac{V}{P}$ = 500 atm•mL
(4) PV = 1/500 atm•mL

57. A cylinder with a tightly fitted piston is shown in the diagram below.



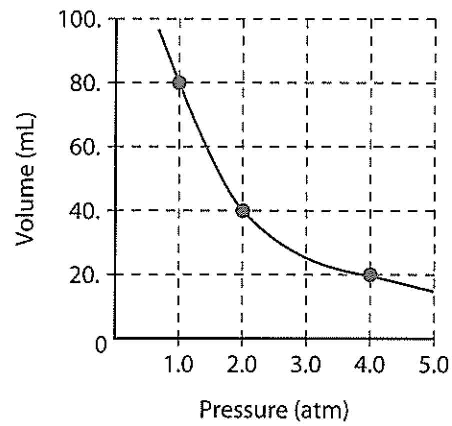
As the piston moves downward, the number of molecules of air in the cylinder

(1) decreases
(2) increases
(3) remains the same

58. A gas has a volume of 1000 mL at a temperature of 20. K and a pressure of 760 mm Hg. What will be the new volume when the temperature is changed to 40.0 K and the pressure is changed to 380 mm Hg?

(1) 250 mL
(2) 1000 mL
(3) 4000 mL
(4) 5600 mL

59. The graph below represents the relationship between pressure and volume of a gas at constant temperature. The product of pressure and volume is constant.



According to the graph, what is the product of pressure and volume (in atm•mL)?

(1) 20. (2) 40. (3) 60. (4) 80.

60. A sample of gas has a volume of 12 liters at 0°C and 380 torr. What will be its volume when the pressure is changed to 760 torr at a constant temperature?

(1) 24 L (2) 18 L (3) 12 L (4) 6.0 L

61. A 2.5 liter sample of gas is at STP. When the temperature is raised to 273°C and the pressure remains constant, the new volume of the gas will be

(1) 1.25 L (2) 2.5 L (3) 5.0 L (4) 10.0 L

62. A gas occupies a volume of 500. mL at a pressure of 380. torr and a temperature of 298 K. At what temperature will the gas occupy a volume of 250. mL and have a pressure of 760. torr?

(1) 149 K
(2) 298 K
(3) 447 K
(4) 596 K

63. A gas at STP has a volume of 1.0 liter. If the pressure is doubled and the temperature remains constant, the new volume of the gas will be

(1) 0.25 L (2) 2.0 L (3) 0.5 L (4) 4.0 L

For each of the following problems, be sure to show your work, use the proper units, and express your answer to the correct number of significant figures.

64. A gas has a volume of 2 liters at 323 K and 3 atmospheres. What will be the new volume if the temperature is changed to 273 K and the pressure is changed to 1 atmosphere?

65. What will be the new volume of 100. mL of gas if the Kelvin temperature and the pressure are both doubled?

66. The pressure exerted on 200. mL of a gas is decreased from 900. torr to 800. torr. What is the new volume of the gas if the temperature remains constant?

Separation of Mixtures

The properties of a mixture's components often provide a means by which they can be separated. Density, molecular polarity, freezing point, and boiling point are a few of the properties that can be used to separate the components of mixtures. In this section you will learn some techniques that can be used to separate the components of mixtures.

Memory Jogger

A mixture is a combination of elements, compounds, or elements and compounds. A solution is a homogeneous mixture. Most mixtures, however, are heterogeneous.

Filtration

Many mixtures are made up of solids in a liquid. The solids are not dissolved in the liquid, but may be suspended. When allowed to stand undisturbed, the solids will settle to the bottom of the liquid. In some cases, you can separate the two components of the mixture by carefully pouring off the liquid without disturbing the solid. This method, though inefficient, can sometimes be used.

A filter is a material that allows small particles to pass through while trapping larger particles on or in the filter material. In essence, the filter is a material containing holes. Particles that are smaller than the holes pass through, while larger particles cannot pass through the holes and are trapped. A mixture of a solid in a liquid can often be separated by filtration. As the mixture passes through the filter, the solid is retained on the filter paper, while the liquid passes through. The substance that passes through the filter is called the filtrate, while the substance remaining on the filter is called the residue.

Filters are also commonly used to separate mixtures of solids and gases. Air conditioners have filters that allow the air to pass through while trapping solids such as lint and dust. Cars and trucks have similar filters.

Some mixtures are composed of two liquids. Two liquids that are not soluble in each other are termed immiscible. Oil and water is an example of such a mixture. Because the oil has a density less than water, the oil rises to the top when the mixture is allowed to stand. In some cases, it is possible to simply pour off the upper layer into a separate container. Figure 4-9 shows a separatory funnel that can be used to separate two liquids that do not dissolve in each other. After the two liquids have been allowed to separate, the valve is opened and the more dense liquid flows from the bottom of the funnel.

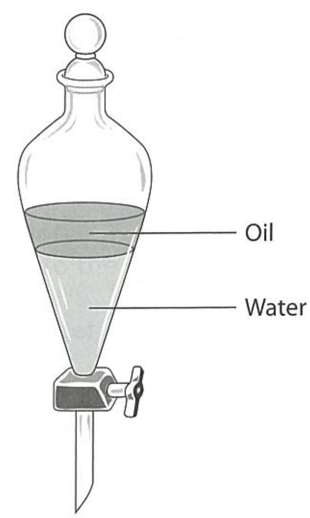


Figure 4-9. Separatory funnel: Two immiscible liquids can be separated with a separatory funnel. When the valve is opened, the denser liquid flows from the funnel.

Practice Questions
for the New York Regents Exam

Directions
Review the Test-Taking Strategies section of this book. Then answer the following questions. Read each question carefully and answer with a correct choice or response.

Part A

1 Which set of properties does a substance such as $CO_2(g)$ have?
(1) definite shape and definite volume
(2) definite shape but no definite volume
(3) no definite shape but definite volume
(4) no definite shape and no definite volume

2 A liquid is poured from a volumetric flask into a beaker. Which of the following is true?
(1) It retains its original volume and shape.
(2) It retains its original volume, but its shape changes.
(3) It retains its original shape, but its volume changes.
(4) Both the volume and shape change.

3 The heat required to change 1 gram of a solid at its normal melting point to a liquid at the same temperature is called the heat of
(1) vaporization (3) reaction
(2) fusion (4) formation

4 Which statement best describes the molecules of H_2O in the solid phase?
(1) They move slowly in straight lines.
(2) They move rapidly in straight lines.
(3) They are arranged in a regular geometric pattern.
(4) They are arranged in a random pattern.

5 As the temperature of a substance rises, the average kinetic energy of the particles making up the substance
(1) increases
(2) decreases
(3) remains the same

6 When a substance melts, it undergoes a process known as
(1) condensation (3) sublimation
(2) fusion (4) vaporization

7 Which sample of CO_2 has a definite shape and a definite volume?
(1) $CO_2(aq)$ (3) $CO_2(s)$
(2) $CO_2(l)$ (4) $CO_2(g)$

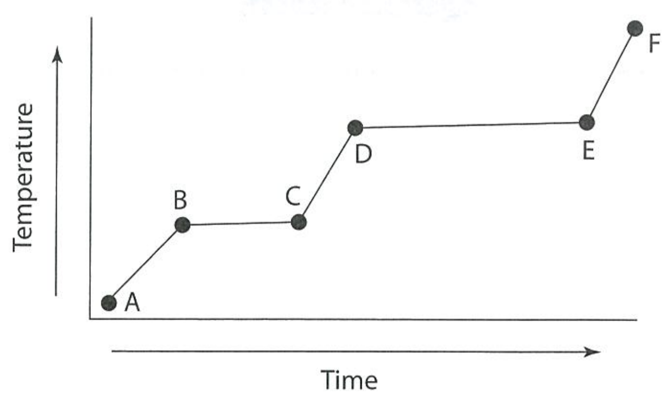
8 Which of the following is a unit of heat energy?
(1) torr (3) gram
(2) degree (4) joule

9 Which energy transfer occurs when ice cubes are placed in water that has a temperature of 45°C?
(1) Chemical energy is transferred from the ice to the water.
(2) Chemical energy is transferred from the water to the ice.
(3) Thermal energy is transferred from the ice to the water.
(4) Thermal energy is transferred from the water to the ice.

Part B–1

10 The graph below represents the uniform heating of a substance, starting below its melting point, when the substance is solid.

Which line segments represent an increase in average kinetic energy?



(1) AB and BC (3) BC and DE
(2) AB and CD (4) DE and EF

11 A liquid's freezing point is −38°C and its boiling point is 357°C. How many Kelvins are there between the boiling point and the freezing point of the liquid?
(1) 319 (3) 592
(2) 395 (4) 668

12 A mixture of sand and table salt can be separated by filtration because the substances in the mixture differ in

(1) boiling point (3) solubility in water
(2) density at STP (4) freezing point

13 Which Celsius temperature is equivalent to 323 K?

(1) 50°C (3) 273°C
(2) 212°C (4) 596°C

14 When steam condenses to water, the surrounding temperature

(1) decreases
(2) increases
(3) remains the same

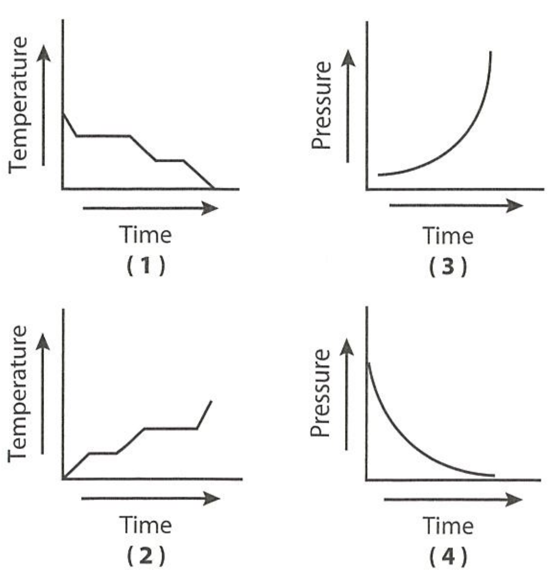
15 Which grouping of the three phases of bromine is listed in order from left to right for increasing distance between bromine molecules?

(1) gas, liquid, solid
(2) liquid, solid, gas
(3) solid, gas, liquid
(4) solid, liquid, gas

16 A sealed, rigid 1.0-liter cylinder contains He gas at STP. An identical sealed cylinder contains Ne gas at STP. These two cylinders contain the same number of

(1) atoms (3) ions
(2) electrons (4) protons

17 Which graph best represents a change of phase from a gas to a solid?



Parts B–2 and C

Base your answers to questions 18 through 20 on the following information.

A student heats a 15.0 gram metallic sphere of unknown composition to a temperature of 98°C. The sphere is transferred to a calorimeter containing 100. mL of water at a temperature of 25.0°C. The student observes that the resulting temperature of both the water and the object is 27.1°C after the object is submerged.

18 Describe, in terms of the object and the water, the flow of heat energy that took place during the experiment.

19 Calculate the amount of heat energy gained by the water in the calorimeter.

20 Using the quantity of heat calculated in the previous question, determine the specific heat of the object.

Base your answers to questions 21 through 23 on the information below.

A student prepared two mixtures, each in a labeled beaker. Enough water at 20.°C was used to make 100 milliliters of each mixture.

Information about Two Mixtures at 20.°C

	Mixture 1	Mixture 2
Composition	NaCl in H_2O	Fe filings in H_2O
Student Observations	• colorless liquid • no visible solid on bottom of beaker	• colorless liquid • black solid on bottom of beaker
Other Data	• mass of NaCl(s) dissolved = 2.9 g	• mass of Fe(s) = 15.9 g • density of Fe(s) = 7.87 g/cm^3

21 Classify *each* mixture using the term "homogeneous" or the term "heterogeneous".

22 Remembering that density is equal to the mass of an object divided by its volume, determine the volume of the Fe filings used to produce mixture 2.

23 Describe a procedure to physically remove the water from mixture 1.

Base your answers to questions 24 through 26 on the information below.

Heat is added to a 200.-gram sample of $H_2O(s)$ to melt the sample at 0°C. Then the resulting $H_2O(l)$ is heated to a final temperature of 65°C.

24 Determine the total amount of heat required to completely melt the sample.

25 Show a numerical setup for calculating the total amount of heat needed to raise the temperature of the water from 0°C to its final temperature.

26 Compare the amount of heat needed to melt the sample at its melting point to the amount of heat needed to vaporize the sample at its boiling point.

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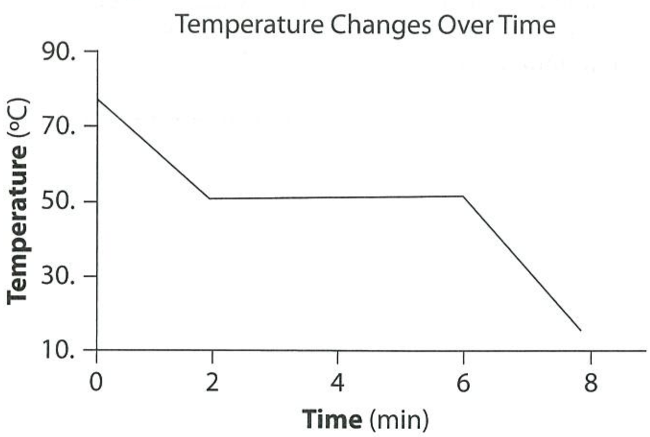
27 A light bulb contains argon gas at a temperature of 295 K and at a pressure of 75 kilopascals. The light bulb is switched on and after 30 minutes, the temperature is 418 K. If the volume of the bulb remains constant, what is the pressure at 418 K?

Use the following information and graph to answer questions 28 through 30.

The graph below shows a compound being cooled at a constant rate starting in the liquid phase at 75°C and ending at 15°C.



28 What is the freezing point of the compound in degrees Celsius?

29 State what is happening to the average kinetic energy of the particles of the sample between minutes 2 and 6.

30 If a total of 780 joules of energy is lost by 25.0 grams of this substance between 2 and 6 minutes, determine the heat of fusion (H_f) of this substance.

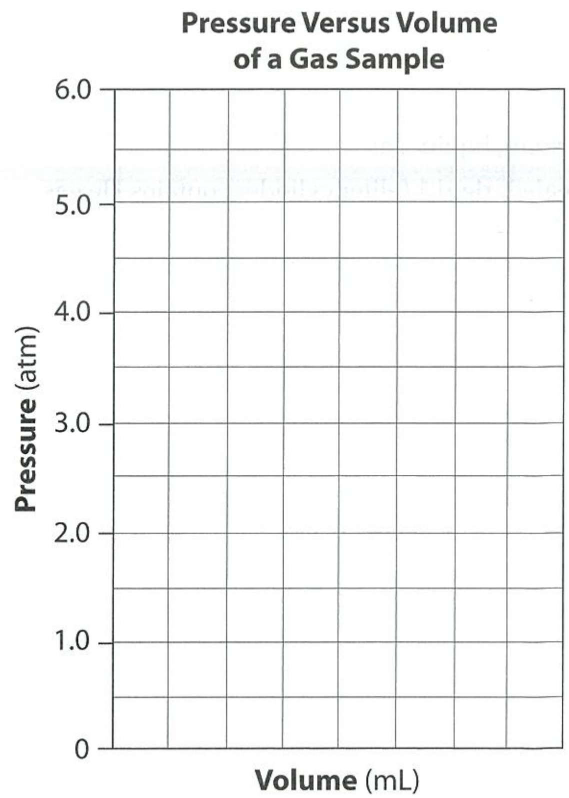
Use the following information to answer questions 31 and 32.

A gas sample is held at a constant temperature in a closed system. The volume of the gas is changed, which causes the pressure of the gas to change. Volume and pressure data are shown in the table. below.

Volume and Pressure of a Gas Sample

Volume (mL)	Pressure (atm)
1200	0.5
600	1.0
300	2.0
150	4.0
100	6.0

31 Mark an appropriate scale on the axis labeled "Volume (mL)", plot the data and connect the points.



32 Based on your graph, what is the pressure of the gas when the volume of the gas is 200 milliliters?