Unit 2 Chemical and Physical Properties

Estimated time: 1 hour

Terminal Objective:
The student will be able to identify the chemical and physical properties of an element or compound.

Enabling Objectives:
The students will

1. Define terms used to identify the chemical and physical properties of an element or compound.
2. Explain the effect of temperature and pressure on chemical and physical properties.
3. Explain how the chemical and physical properties will influence a risk assessment during an emergency response.

Chemical and Physical Properties
The chemical properties of substances determine the substance’s ability to undergo reactions and form new substances; these properties are only observed in a chemical reaction.

The physical properties are features that can be observed without a chemical reaction; for example, attributes such as color, density or smell.

In the discussion to follow we will consider the following features and explain how they relate to one another, as well as how they relate to the underlying composition of a chemical:

- Physical state and changes in that physical state or “phase changes”
- The variables that affect the phase changes (molecular weight, hydrogen bonding, and molecular shape)
- Vapor pressure and equilibrium
- Volatility
- Flashpoint, flammable range, and ignition temperature
- Specific gravity
- Vapor density
- Solubility
- pH

We will consider the three basic states of matter:

- Solids
- Liquids
- Gases
Solids, as discussed earlier, have a specific mass and shape and occupy a specific volume. Liquids also have a specific mass and occupy a specific volume, but not a specific shape. Liquids assume the shape of the container. Gases have mass, but do not have a specific volume or shape.

The chemical and physical properties are directly influenced by the state that the substances are in during the chemical reaction solid, liquid or gas. For example, many solid and liquid fuels must be converted to a gas before they will ignite and burn.

**Physical State**

Molecular weight can be defined as the weight of an atom or as the sum of the atomic weights of the atoms making up a substances molecular formula. The molecular formula for carbon dioxide is CO$_2$. By adding the atomic weights of all the atoms that make up the molecular formula we can calculate its molecular weight. According to its formula, CO$_2$ is composed of 1 atom of carbon (atomic weight = 12) and 2 atoms of oxygen (atomic weight = 16 each). Therefore atomic weight of carbon dioxide is 44.

In the following sections, we discuss how molecular weight plays a role in the chemical and physical properties of a substance.

**Knowledge review**

*Choose the correct response to the question below.*

The atomic weight of nitrogen is 14 and the atomic weight of hydrogen is 1. What is the molecular weight of ammonia with a molecular formula of NH$_3$?

- a. 15
- b. 16
- c. 17
- d. 18

The correct answer is 17.

Rationale: According to the periodic table nitrogen has an atomic weight of 14 and hydrogen an atomic weight of 1. Each molecule of ammonia has 1 nitrogen atom and 3 hydrogen atoms; therefore, the atomic weight of ammonia is equal to 14 + 3 = 17 atomic mass units.

**Physical State**

- The physical shape of a substance plays an important role in determining its chemical and physical properties.
- A molecule may assume many shapes based on its configuration, and the shape helps determine its physical and chemical characteristics.
Temperature / Pressure and the Physical State
Most materials can exist in more than one physical state. A common example is ordinary water. Liquid water will freeze and become a solid at 32°F (0°C) at standard atmospheric pressure (1 atmosphere). The temperature of 32°F is known as the freezing point for this substance.

This temperature can also be called its melting point. For water, the freezing point and melting point are identical; although there are some exceptions, this is true for most other substances.

At 212°F (100°C), liquid water begins to boil at standard atmospheric pressure (sea level) as it begins a transition or phase change from a liquid state to a vapor or gas. The specific temperature at which a liquid boils under a given set of environmental conditions is known as its boiling point.

At ordinary atmospheric pressure and temperature, some substances can change from a solid state to a vapor state without becoming a liquid first. This process is called sublimation. Frozen carbon dioxide (dry ice) will change directly into a vapor from its solid state. Carbon dioxide can become a liquid only in confinement under special conditions.

Materials also have what is called a "triple point." The triple point is the temperature and pressure at which a material can exist in all three physical states simultaneously. This can be expressed in a graphic.

Temperature
Temperature is an indication of the amount of heat or thermal energy held within an object or substance, the greater the amount of heat (temperature), the greater the molecular movement, that is, the random movement in the particles that make up the substance.

As the movement increases, so does the distance between its constituent parts which may result in a change in physical state. Conversely, cooling decreases movement and decreases the molecular distance which may result in a change in physical state.

A temperature scale is used to measure heat. The Kelvin Scale is the principal temperature scale used in science and engineering. In the United States, however, the Fahrenheit Scale is commonly used. In the Fahrenheit Scale temperature is expressed as °F where water boils at 212°F and freezes at 32°F. The Celsius Scale (expressed as °C) is used in the rest of the world. Water boils at 100°C and freezes at 0°C.

Knowledge review
Choose the correct response to the question below.

Water has a boiling point of 212 degrees Fahrenheit (°F) at 1 atmosphere that is equal to 100 degrees in the Celsius temperature scale.

a. True
b. False

The correct answer is true.
Rationale: Temperature scales are used to measure heat. The boiling point of 212 degrees Fahrenheit (°F) at 1 atmosphere

**Pressure**
Pressure (including ambient atmospheric pressure) is another variable affecting physical states and state changes. Pressure is an effect which occurs when a force is applied on a surface expressed as the amount of force per unit area. For example, pressure is commonly expressed as pounds per square inch (psi).

Atmospheric pressure controls the boiling point of substances that exist in a liquid state. In a vacuum such as outer space, only solids and gases exist.

As pressure decreases, the amount of vaporization increases at a given temperature. As pressure increases, the amount of vaporization decreases at a given temperature.

In the United States pressure is expressed as pounds per square inch, bars or inches of mercury. In the metric system, pressure is expressed as Pascal (Pa); one Pascal is equal to one Newton per square meter (1 psi = 6895 Pa).

**Knowledge review**
*Choose the correct response to the questions below.*

1. As the temperature of a liquid increases, the rate of vaporization of that liquid also increases.
   a. True
   b. False

   The correct answer is true.

   Rationale: As temperature increases at a given pressure, the rate of vaporization increases. As pressure decreases at a given temperature, the rate of vaporization increases.

2. As pressure increases over the surface of a liquid, the rate of vaporization decreases at a given temperature.
   a. True
   b. False

   The correct answer is true.

   Rationale: As pressure increases at a given temperature, the rate of vaporization decreases. As pressure decreases at a given temperature, the rate of vaporization increases.

**Molecular Weight**
A third variable affecting changes in physical state is **molecular weight**. For the purposes of this class, the terms molecular weight and molecular mass will be considered equivalent. Molecular weight is calculated by summing the atomic weights of the atoms making up the substance’s **molecular formula**.
The molecular formula of water is H₂O by adding the atomic weights of all the atoms in water (water is composed of 2 atoms of hydrogen each having an atomic weight of 1 and 1 atom of oxygen with an atomic weight of 16) we can calculate the atomic weight of water which is equal to 18 atomic mass units (AMU). The AMU is the unit used to indicate the mass (weight) of molecule.

**Molecular Shape**
The shape of the molecule (molecular geometry), is the physical arrangement of the atoms that form the compound in three dimensions. This geometry determines many chemical and physical properties such as polarity, color, reactivity etc.

Molecules may be composed of atoms that from a straight chain or maybe branched with small fragments coming off the main chain. Generally, branched compounds can crowd into a smaller space because of their smaller physical size. Cyclic compounds have a roughly triangular or circular shape.

**Electronegativity**
Electrons are not always shared equally between two bonding atoms. One atom might exert more of an attractive force on the electron than the other atom forming the bond. This "pull" is known as electronegativity, and it is a measure of an atom’s attraction for electrons.

**Knowledge review**
*Choose the correct response to the question below.*

The attractive force an atom exerts on its electrons is call ____________

a. electronegativity  
b. electropositivity  
c. polarity  
d. none of the above

The correct answer is electronegativity.

Rationale: Atoms on the right side of the periodic table have a stronger attraction for their electrons than those on the far left. That attraction is called electronegativity.

**Polarity**
The positive and negative electric charge on the molecule causes an electrical attraction between opposite charges on the surface of the molecule. This electrical attraction alters the chemical and physical properties of the substance.

Hydrogen bonding produces the most pronounced effect and is therefore the strongest form of polarity. Water is not a gas at normal temperature and pressure because of the hydrogen bonding within its structure.
**Vapor pressure**

Vapor pressure is the force exerted by molecules leaving the surface of a liquid and entering the atmosphere. Vapor pressure is a measure of the tendency of a material to change into the vapor state. Vapor pressure also occurs with solids that sublime. It is present in all liquids in varying degrees.

Molecular movement provides the force of vapor pressure and there is a direct relationship between temperature and vapor pressure.

This relationship can be stated as follows:

- The lower the temperature of the substance, the lower its vapor pressure.
- The greater the temperature of the substance, the greater its vapor pressure.

Vapor pressure is measured in the NIOSH Pocket Guide, at the standard temperature of 68ºF.

**Knowledge review**

*Complete the statement below.*

The data on vapor pressure for chemicals listed in the NIOSH Pocket Guide are based on a temperature of ___ degrees Fahrenheit.

- a. 32
- b. 68
- c. 100
- d. 212

The correct answer is 68.

Rationale: Vapor pressure is measured in the NIOSH Pocket Guide, at the standard temperature of 68ºF

**Vapor pressure**

**Molecular Weight and Polarity**

The molecular weight of a substance plays a major role in vapor production.

- Low molecular weight substances have the highest vapor pressure.
- High molecular weight substances have the lowest vapor pressure.

The polarity of the substance also affects its vapor pressure.

- Polar substances have lower vapor pressure than non-polar substances of the same molecular weight.
Hydrogen Bonding

The effect of hydrogen bonding is to reduce the degree of molecular movement significantly and thus reduce the vapor pressure. For this reason, hydrogen-bonded substances have the lowest vapor pressure in comparison to non-polar, and even polar substances, of the same molecular weight.

Shape

Straight chain compounds have the lowest vapor pressure, especially in larger compounds, because molecules tend to intertwine. Branched compounds have the highest vapor pressure because of their smaller molecular size. Cyclic compounds have a mid-level vapor pressure.

Units of Measurement for Pressure

There are several units that can be used for measuring pressure.

All of the following units for measuring standard atmospheric pressure (1 atmosphere) are equivalent:

- 14.7 psi
- 760 millimeters of mercury (mm Hg)
- 29.92 inches of mercury
- 1 bar
- 101.33 kiloPascals (kPa)

Chemists use a standard set of conditions for documenting experimental measurements. Chemical and physical properties published in reference material are based on standard temperature and pressure. Standard temperature or room temperature is 68°F (20°C). Standard pressure is 760 mmHg (1 atmosphere) pressure.

Below are the vapor pressures for some common chemicals listed in mmHg:

- fuel oil #4 - 2 mm Hg
- water - 25 mm Hg
- gasoline and acetone - 180 mm Hg
- ethyl ether - 430 mm Hg

Boiling Point

The boiling point is the temperature at which the substance's vapor pressure equals atmospheric pressure. The shape of an atom, molecule, or ion affects the boiling point.

- Straight chain compounds have the highest boiling point.
• Branched compounds have the lowest boiling point.
• Cyclic compounds are in between.

Flash Point / Fire Point

Flash Point

Given an ignition source, flash point is the lowest temperature at which a volatile liquid can vaporize to form an ignitable mixture in air. The flash point is related directly to the boiling point. This direct relationship means that if a substance has a low boiling point, it has a correspondingly low flash point. Likewise, a high boiling point means a high flash point.

Fire Point

The fire point is a higher temperature than the flash point. Fire point is defined as the temperature at which a volatile liquid will produce enough vapor that once the vapor is ignited, it will continue to burn.

Molecular Weight / Flash Point

Molecular weight is a factor affecting flash point.

• Low molecular weight, low flash point
• High molecular weight, high flash point

Specific Gravity

Specific gravity is the ratio of the weight or density of a substance to water. The specific gravity of a substance is determined by dividing the weight of a substance by the weight of water.

Water weighs 62.4 pounds per cubic foot (lb./ft³) of volume, which is equal to 1.0 gram per cubic centimeter (g/cm³).

Water is assigned a specific gravity of 1, and it serves as the reference point for all other materials. Substances that weigh less than 62.4 lb./ft³ would equal a number less than 1, and substances that weigh more than 62.4 lb./ft³ would equal a number greater than 1.

Buoyancy is related to specific gravity. Substances with a specific gravity less than 1 tend to float in water, while substances with a specific gravity greater than 1 tend to sink when placed in water.
Knowledge review

Complete the statement below

Water is assigned a specific gravity of 1; according to the NIOSH Pocket Guide, gasoline has a specific gravity of 0.76 at 60°F. If gasoline is spilled into a lake, the gasoline will _________.

a. float  
   b. sink  
   c. mix  
   d. dissolve

The correct answer is float.

Rationale: The buoyancy of a substance is related to its specific gravity, substances with a specific gravity less than 1 tend to float in water, while substances with a specific gravity greater than 1 tend to sink.

Vapor Density

Vapor density is the ratio of the density of a pure gas or vapor to the density of air. This ratio is based upon the assumption that air has a value of 1.0. Thus, vapors with a vapor density less than 1.0 are considered lighter than air in the natural environment, while those with values greater than 1.0 are heavier than air. If temperatures are not known, vapor density can be calculated using molecular weight.

Knowledge review

Complete the statement below

Air has a molecular weight of approximately 29 and is assigned the vapor density of 1. According to the NIOSH Pocket Guide, Benzene has a molecular weight of 78.1, and a vapor density of 2.7. Benzene vapors in air would typically _____ and follow the terrain.

a. float  
   b. sink  
   c. dissolve  
   d. react violently and cause a fire

The correct answer is sink.

Rationale: Vapors or gases with vapor density less than 1.0 are considered lighter than air, while those with values greater than 1.0 are heavier than air.

Solubility

Solubility is defined as the ability of some liquids (solvents) to dissolve a finite amount of another substance (solute) before the solution becomes saturated at 68°F. Sugar and salt dissolve in water, alcohol mixes readily with water, and even gases like carbon dioxide dissolve in water to form seltzer or
carbonated water. Each of these cases is an example of a solid, liquid, or gas that can dissolve in water; these substances are said to be water soluble.

For example, only a certain amount of ordinary table salt can be dissolved in water before any additional salt will simply sink to the bottom of the glass. In the case of table salt, 35.7 grams of salt will dissolve in 100 grams of water at a temperature of 32°F. This amount will increase to approximately 39 grams of salt if the water is heated to 212°F. Solubility is a function of the temperature of the solvent.

Miscibility refers to the process where substances will dissolve in any proportion in a liquid. For example, any amount of ethanol can be added to a glass of water and the alcohol will not form a separate layer or phase. Insoluble or immiscible substances, will not dissolve into each other, and will form a distinct layer when mixed. Numerous factors come into play when determining a material’s solubility; for our purposes, polarity and hydrogen bonding are key factors.

**Acids/Bases**

In chemistry, pH is the value taken to represent the acidity or basicity of a solution. The pH scale is a scale indicating the ratio of the number of free hydrogen (H+) ions or hydroxyl (OH-) ions compared to the number of water molecules.

The more hydrogen ions there are in the aqueous solution, the more acidic the solution. The more hydroxyl ions there are, the more base the solution.

Pure water is neutral with a pH of 7. A solution with a pH below 7 is acidic while a solution with a pH above 7 is basic.

**Knowledge review**

*Choose the correct response to the question below.*

A solution is considered acidic if the pH is less than 7. A solution with a pH of 10 is called a base.

a. The first statement is true but the second statement is false.
b. The first statement is false but the second statement is true.
c. Both statements are true.
d. Both statements are false.

The correct answer is both statements are true.

Rationale: Pure water is neutral with a pH of 7. A solution with a pH below 7 is acidic while a solution with a pH above 7 is basic.

**Strength**

Strength is based on how easily an acid or base ionizes in water. Some examples of strong acids are:

- hydrochloric acid.
- nitric acid.
- sulfuric acid (battery acid).
Concentration

Percent concentration by mass is the weight of the acid divided by the total weight of the solution (acid and water). This calculation will produce the concentration of an acid by mass.

Risk Assessment

Hazard Risk assessment is the process of estimating the chances of a substance causing a harmful effect in the responder, the population or the environment.

At least three concepts are involved in assessing risk:

- **Hazard** – any situation that has the potential to cause damage
- **Probability** – The likelihood that the particular hazard will result in damage or injury
- **Severity** – An estimation of the severity of the potential problem.

Knowledge review

*Choose the correct response to the question below.*

Which of the following concepts are evaluated when a firefighter is conducting a risk assessment?

- a. Probability
- b. Severity
- c. Hazard
- d. All the above

The correct answer is all of the above.

**Rationale:** Hazard Risk Assessment is the process of estimating the chances of a substance causing a harmful effect based on the following three factors: the hazard posed by the substance, the probability of the event occurring and the potential severity of the event.

Summary

In this unit, you have learned:

- The definition of physical properties.
- The definition of chemical properties.
- The influence of chemical and physical properties on risk assessment.