

# Diving Physics



# Sources

- Joiner, J.T. (ed.). 2001. NOAA Diving Manual - Diving for Science and Technology, Fourth Edition. Best Publishing Company, Flagstaff, AZ.
- Reference Materials:
  - In conjunction with this presentation, refer to:
    - NOAA Diving Manual Chapter 2



# Objectives

- After completing this training module you will be able to:
  - Differentiate among atmospheric, hydrostatic, absolute, gauge, and partial pressures
  - Define density and specific gravity
  - State the differences between freshwater and seawater important to diving



# Objectives

- After completing this training module you will be able to:
  - Perform basic calculations involving the units of measurement and temperature commonly used in diving
  - Define Archimedes' Principle and describe the three states of buoyancy



# Objectives

- After completing this training module you will be able to:
  - Differentiate between the gases used in, or associated with, diving
  - State and apply Boyle's Law, Charles' /Gay-Lussac's Law, Dalton's Law, Henry's Law, and the General Gas Law



# Objectives

- After completing this training module you will be able to:
  - Explain how moisture in the breathing gas and humidity impact the diver and the diver's equipment
  - Explain how the properties of light and sound are affected by diving



# General

- Physics is the field of science dealing with matter and energy and their interactions
- This chapter explores physical laws and principles that pertain to the diving environment and its influence on the diver



# General

- The principles of physics provide the keystone for understanding the reasons for employing various diving procedures





# Pressure

- Pressure is force acting on a unit area
  - Pressure = force / area
  - $P = F/A$
- In the USA pressure is typically measured in pounds per square inch (psi)
- A diver, at any depth, must be in pressure balance with the forces at that depth



# Atmospheric Pressure

- This is the pressure exerted by the earth's atmosphere
- At sea level it is equal to 14.7 psi, or one atmosphere (atm)
- It decreases with altitude above sea level
  - For example, at 18,000 ft atmospheric pressure is 7.35 psi or half that at sea level



# Hydrostatic Pressure

- Pressure due to the weight of water is called “hydrostatic pressure”
- The deeper the dive, the greater the weight of the water, the greater the hydrostatic pressure
- Hydrostatic pressure affects the diver from all sides equally



# Hydrostatic Pressure

- In seawater hydrostatic pressure increases at a rate of 0.445 psi per foot
- Hydrostatic pressure reaches one atm at 33 ft in seawater, and increases by one atm for every additional 33 ft thereafter



# Hydrostatic Pressure

- In freshwater hydrostatic pressure increases by 0.432 psi per foot
- Hydrostatic pressure reaches one atm at 34 ft in freshwater and increases by one atm for every additional 34 ft thereafter



# Absolute Pressure

- The sum of atmospheric pressure plus hydrostatic pressure equals “absolute pressure”



# Absolute Pressure

- Absolute pressure can be expressed as:  
“psia” (pounds per square inch absolute),  
“ata” (atmospheres absolute), “fswa” (feet  
of seawater absolute), “ffwa” (feet of  
freshwater absolute), or “mmHga”  
(millimeters of mercury absolute)



# Gauge Pressure

- The difference between atmospheric pressure and the pressure being measured is “gauge pressure”
- It can be expressed as psig (pounds per square inch gauge)
- The zero reading on a cylinder pressure gauge at sea level is actually equal to 14.7

psia  
NOAA

- Gauge pressure + 14.7 = ata





# Partial Pressure

- The total pressure of a mixture of gases is equal to the sum of the partial pressure of each gas in the mixture
- For our purposes air is composed of 21% oxygen and 79% nitrogen
- Thus, the partial pressure at sea level of nitrogen is 0.79 ata, and oxygen is 0.21 ata



# Density

- Density can be defined as weight per unit volume
  - Density = Weight / Volume
  - $D = W / V$
- Gas density is related to absolute pressure
- As depth increases, the density of the breathing gas increases and thus it becomes heavier per unit volume



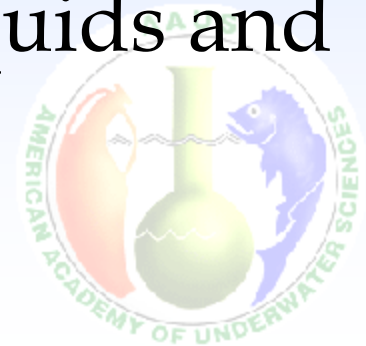
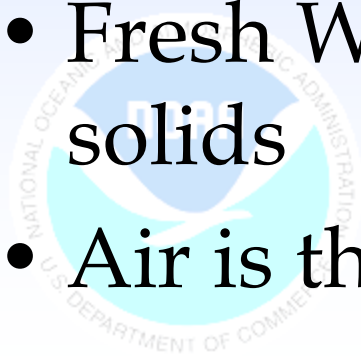
# Density

- Freshwater has a density of 62.4 pounds per cubic foot
- Seawater has a density of 64 pounds per cubic foot
- As a result, freshwater floats on top of seawater and a diver floats more easily in seawater than in freshwater



# Specific Gravity

- Specific gravity is the ratio of the weight of a given volume of a substance to that of an equal volume of another substance
- The density of a substance divided by the density of the standard for a group of substances equals the specific gravity of the substance
- Fresh Water is the standard for liquids and solids
- Air is the standard for gases



# Specific Gravity

- Substances that are more dense than freshwater have a specific gravity greater than 1.0
- The specific gravity of seawater is  $64/62.4 = 1.026$



# Freshwater

- $H_2O$  is odorless, tasteless and very slightly compressible
- It freezes at  $32^{\circ}F$ , and boils at  $212^{\circ}F$
- In its purest form, it is a poor conductor of electricity



# Seawater

- Seawater contains almost every substance known
- The most abundant chemical is sodium chloride (common table salt)
- Seawater is a good conductor of electricity



# pH

- The pH of an aqueous solution expresses the level of acids or alkalis present
- The pH of a liquid can range from 0 (strongly acidic) to 14 (strongly alkaline); a pH of 7 is neutral





# Units of Measurement

- There are two systems for specifying force, length and time: English and Metric (also known as the International System of Units or SI)



# Units of Measurement

- The English System is based on the pound (lb), the foot (ft), and the second (s)
- The International System is based on the kilogram (kg), the meter (m), and the second (s)



# Length

- 1 meter equals 39.37 inches
- 1 meter equals 3.28 feet (i.e.,  $39.37 / 12$ )
- Covert 10 feet to meters:
  - $10 \text{ ft} / 3.28 \text{ ft} = 3.05 \text{ m}$
- Convert 10 meters to feet:
  - $10 \text{ m} \times 3.28 \text{ ft} = 32.8 \text{ ft}$



# Area

- In both the English and SI system, area is expressed as a length squared
- For example:
  - A room that is 12 feet by 10 feet would have an area of 120 square feet (12 ft x 10 ft)
  - A room that is 3.66 m by 3.05 m would have an area of 11.16 square meters



# Volume

- Volume is expressed in units of length cubed
- Length x Width x Height = cubic feet (ft<sup>3</sup>) or cubic meters (m<sup>3</sup>)
  - The English System, in addition to ft<sup>3</sup>, uses other units of volume such as gallons
  - The SI uses the liter (L). One liter = 1000 cubic centimeters (cm<sup>3</sup>) or 0.001 cubic meters (m<sup>3</sup>), which is one milliliter (mL)



# Weight

- The standard measure of weight in the English System is the pound (lb)
- The standard measure of weight in the International System of Units is the kilogram (kg)
- One liter of water at 4°C weighs 1 kg or 2.2 lbs



# Weight

- Convert 180 pounds to kilograms:

$$180 \text{ lbs} / 2.2 \text{ lbs} = 81.8 \text{ kg}$$

- Convert 82 kilograms to pounds:

$$82 \text{ kg} \times 2.2 \text{ lbs} = 180.4 \text{ lbs}$$



# Temperature

- Heat is associated with the motion of molecules
- The more rapidly the molecules move, the higher the temperature
- Temperature is usually measured either with the Fahrenheit ( $^{\circ}\text{F}$ ) scale or with the Celsius (centigrade) scale ( $^{\circ}\text{C}$ )





# Temperature

- Temperature must be converted to absolute when the gas laws are used
- The absolute temperature scales are Rankine (R) or Kelvin (K), and are based on absolute zero
- Note the degree symbol ( $^{\circ}$ ) is only used with Celsius and Fahrenheit temperatures



# Temperature

- The Fahrenheit (°F) and Rankine (R) temperature scales are used in the English System
- To convert Fahrenheit to absolute temperature Rankine:

$$^{\circ}\text{F} + 460 = \text{R}$$



# Temperature

- The Celsius (C) and Kelvin (K) temperature scales are used in the International System of Units
- To convert from Celsius to absolute temperature Kelvin:

$$^{\circ}\text{C} + 273 = \text{K}$$



# Buoyancy

- Archimedes' Principle:

“Any object wholly or partly immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced by the object”



# Buoyancy

- Buoyancy is termed “Positive” when the weight of the displaced fluid is greater than the submerged object (i.e., object floats)
- Buoyancy is termed “Negative” when the weight of the displaced fluid is less than the weight of the submerged object (i.e., object sinks)
- If the weight of the object is equal to the weight of the fluid displaced the buoyancy is “Neutral” (i.e., object is suspended)



# Buoyancy

- Buoyancy is dependent upon the density of the surrounding liquid – the greater the density the greater the buoyancy force
- Seawater has a density of 64 pounds per cubic foot
- Freshwater has a density of 62.4 pounds per cubic foot



# Gases Important for Diving

- Atmospheric Air
- Oxygen (O<sub>2</sub>)
- Nitrogen (N<sub>2</sub>)
- Helium (He)
- Carbon Dioxide (CO<sub>2</sub>)
- Carbon Monoxide (CO)
- Argon (Ar)
- Neon (Ne)
- Hydrogen (H<sub>2</sub>)



# Air

- Atmospheric Air is the most common gas breathed underwater
- It is composed of approximately:
  - 78% Nitrogen
  - 21% Oxygen
  - 1% other gases





# Oxygen (O<sub>2</sub>)

- Oxygen is required for human life
- However, under certain conditions it can be toxic
- Oxygen is required for fire



# Oxygen (O<sub>2</sub>)

- O<sub>2</sub> comes in 3 basic grades:
  - Aviator's Oxygen (Grade A) - ultra dry
  - Medical/Industrial Oxygen (Grade B)
  - Technical Oxygen (Grade C) - may contain contaminants - not recommended for diving (but ok for treating decompression sickness if no other O<sub>2</sub> available - better than nothing)



# Nitrogen (N<sub>2</sub>)

- Is the largest proportion of the air we breathe, but plays no part in metabolism
- Nitrogen plays the major role in decompression



# Nitrogen (N<sub>2</sub>)

- As the partial pressure of N<sub>2</sub> increases with depth, it produces an intoxicated state, nitrogen narcosis (also known as “inert gas narcosis”), that is characterized by loss of judgment and disorientation



# Helium (He)

- Helium is used extensively in deep diving
- It does not cause the problems associated with nitrogen narcosis
- It has a lower density than nitrogen that reduces breathing resistance
- The disadvantages of He include “Donald Duck” voice and heat loss due to its high thermal conductivity



# Carbon Dioxide (CO<sub>2</sub>)

- CO<sub>2</sub> is a natural by-product of metabolism
- Excess carbon dioxide can cause unconsciousness that can be fatal in divers



# Carbon Dioxide (CO<sub>2</sub>)

- Elevated CO<sub>2</sub> levels may further predispose a diver to nitrogen narcosis, oxygen toxicity, and decompression sickness



# Carbon Monoxide (CO)

- CO is a poisonous gas which interferes with the blood's ability to carry oxygen





# Carbon Monoxide (CO)

- CO is produced by the incomplete combustion of fuels and is found in the exhaust of internal-combustion engines and overheated oil-lubricated compressors
- The effects can be lethal



# Argon (Ar)

- Argon has narcotic properties and a density which make it inappropriate as a breathing gas
- It is frequently used to inflate dry suits because its higher density reduces conduction of heat



# Neon (Ne)

- Neon causes less voice distortion than helium and has lower thermal conductivity
- However, it is expensive and causes increased breathing resistance under work load



# Hydrogen (H<sub>2</sub>)

- Hydrogen is readily available and produces less breathing resistance at depth than other gases
- Its major disadvantage is that it is explosive



# Gas Laws

- Gases are subject to three interrelated factors: pressure, volume, and temperature
- A change in one factor results in a measurable change in the others
- This change is true with pure gases or a gas mixture
- The relationships among these three factors have been defined as the gas laws

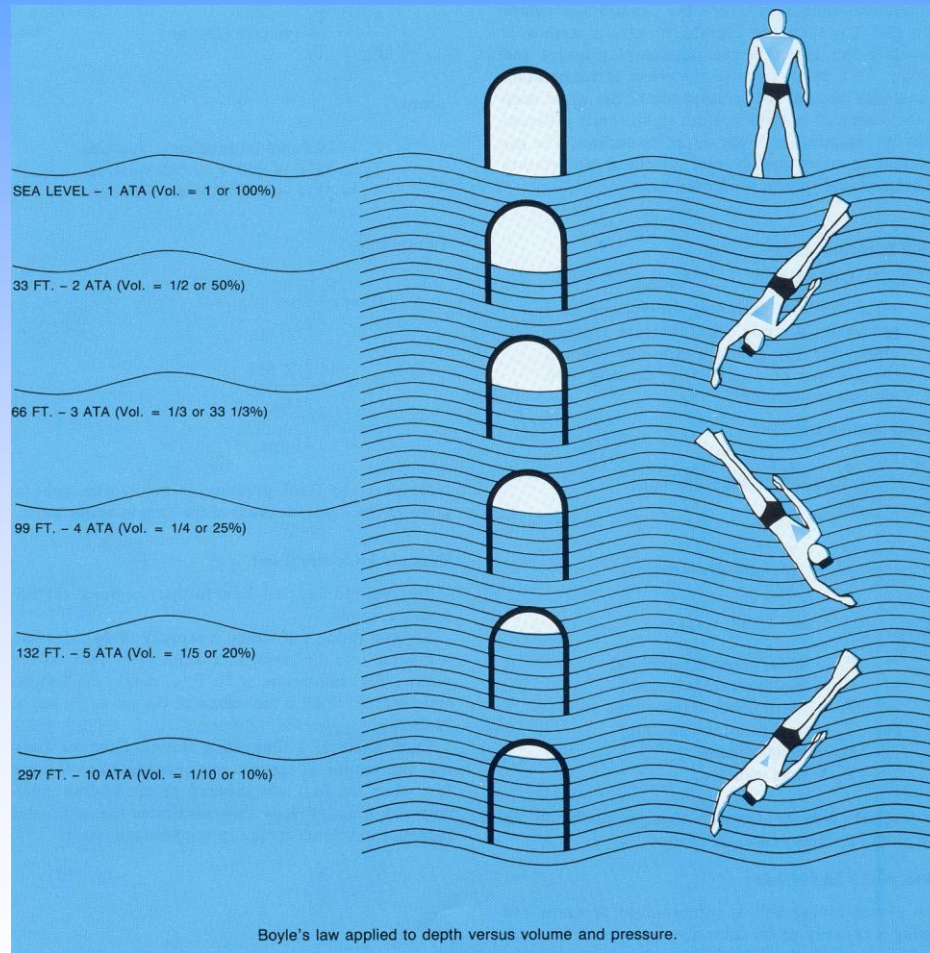


# Boyle's Law

- “For any gas at a constant temperature, the volume of the gas will vary inversely with the pressure”



# Boyle's Law Applied:



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# Boyle's Law

- An open-bottom diving bell containing 24 cubic feet of gas is lowered from the surface to a depth of 33 fsw. No gas is supplied or lost during descent. Calculate the volume of air space in the bell at 33 fsw.





# Boyle's Law

- Boyle's Equation:  $P_1V_1=P_2V_2$ 
  - $P_1$  = initial pressure surface absolute
  - $V_1$  = initial volume in cubic feet (ft<sup>3</sup>)
  - $P_2$  = final pressure absolute
  - $V_2$  = final volume in cubic feet (ft<sup>3</sup>)



# Boyle's Law

- An open-bottom diving bell containing 24 cubic feet of gas is lowered from the surface to a depth of 33 fsw
  - $P_1 =$  Surface or 1 ata
  - $V_1 = 24 \text{ ft}^3$
  - $P_2 = 33 \text{ fsw}$  or 2 ata
  - $V_2 =$  Unknown



# Boyle's Law

$$V_2 = \frac{P_1 V_1}{P_2}$$



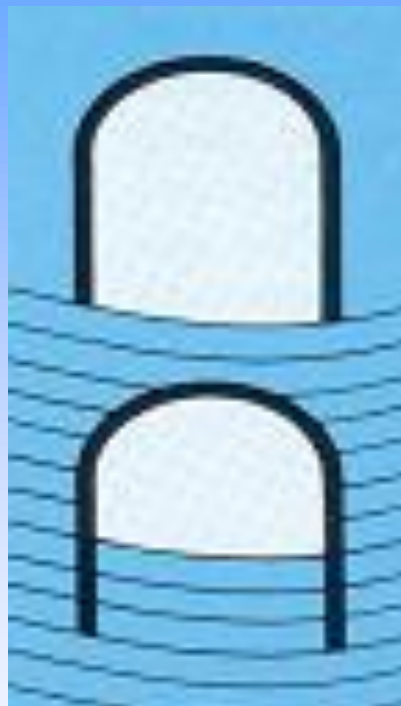
# Boyle's Law

$$V_2 = \frac{1 \text{ ata} \times 24 \text{ ft}^3}{2 \text{ ata}}$$



# Boyle's Law

$$V_2 = 12 \text{ ft}^3$$



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# Charles'/ Gay-Lussac's Law

- “For any gas at a constant pressure, the volume of the gas will vary directly with the absolute temperature or for any gas at a constant volume, the pressure of the gas will vary directly with the absolute temperature”



# Charles' Law - Volume Change

- Our diving bell also experienced a temperature change from  $80^{\circ}\text{F}$  to  $45^{\circ}\text{F}$
- Compute the volume change



# Charles' Law - Volume Change

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$





# Charles' Law - Volume Change

- Charles' Equation:  $V_1/V_2 = T_1/T_2$ 
  - $V_1 =$  volume at 33 ft = 12 ft<sup>3</sup>
  - $T_1 = 80^\circ\text{F} + 460 = 540$  Rankine
  - $T_2 = 45^\circ\text{F} + 460 = 505$  Rankine
  - $V_2 =$  Unknown



# Charles' Law - Volume Change

$$V_2 = \frac{V_1 T_2}{T_1}$$



# Charles' Law - Volume Change

$$V_2 = \frac{12 \text{ ft}^3 \times 505 \text{ R}}{540 \text{ R}}$$



# Charles' Law - Volume Change

$$V_2 = 11.22 \text{ ft}^3$$



# Charles' Law - Volume Change

- The volume in the diving bell was reduced an additional  $0.78 \text{ ft}^3$  due to the decrease in temperature



# Gay-Lussac's Law - Pressure Change

- A scuba cylinder contains 3,000 psig (3,014.7 psia) at 64°F. It is left in the sun on a hot summer day. What will the cylinder pressure be if the temperature of the air inside reaches 102°F?



# Gay-Lussac's Law - Pressure Change

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$



# Gay-Lussac's Law - Pressure Change

- $P_1 = 3,014.7$
- $T_1 = 64^\circ\text{F} + 460 = 524$  Rankine
- $T_2 = 102^\circ\text{F} + 460 = 562$  Rankine
- $P_2 = \text{Unknown}$





# Gay-Lussac's Law - Pressure Change

$$P_2 = \frac{P_1 T_2}{T_1}$$



# Gay-Lussac's Law - Pressure Change

$$P_2 = \frac{3,014.7 \times 562 \text{ R}}{524 \text{ R}}$$



# Gay-Lussac's Law - Pressure Change

$$P_2 = 3,233.3 \text{ psia}$$



# Gay-Lussac's Law - Pressure Change

- To convert to gauge pressure, subtract 14.7

$$3,233.3 \text{ psia} - 14.7 \text{ psi} = 3,218.6 \text{ psig}$$



# Dalton's Law

- “The total pressure exerted by a mixture of gases is equal to the sum of the pressures of each of the different gases making up the mixture, with each gas acting as if it alone was present and occupied the total volume”



# Dalton's Law

- $P_t = PP_1 + PP_2 + PP_3, \text{ etc.}$ 
  - $P_t$  = Total Pressure
  - $PP_1, \text{ etc.}$  = Partial pressure of first gas, etc.
- Partial pressure of a given quantity of a particular gas is the pressure it would exert if it alone occupied the total volume



# Dalton's Law

- The figure  $P_x$  is used to indicate partial pressure. The subscript  $x$  represents the specific gas
- To determine the partial pressure of a gas mixture:

$$P_x = \text{Gas \%} \times P_t$$



# Dalton's Law

- A container is filled with air at a total pressure of 14.7 psi. What is the partial pressure of the nitrogen?
- For this example air consists of:

$$\text{N}_2 = 78.08\%$$

$$\text{O}_2 = 20.95\%$$

$$\text{CO}_2 = 0.03\%$$

$$\text{Other gases} = 0.94\%$$





# Dalton's Law

$$P_x = \text{Gas \% (decimal)} \times P_t$$

$$PN_2 = 0.7808 \times 14.7 \text{ psi}$$

$$PN_2 = 11.478 \text{ psi}$$



# Dalton's Law

Expressed in atmospheres:

$$P_{N_2} = 0.7808 \times 1.0 \text{ atm}$$

$$P_{N_2} = 0.7808 \text{ atm}$$



# Dalton's Law

What is the partial pressure of nitrogen within a scuba cylinder of air filled to 2,000 psi?

$$PN_2 = 0.7808 \times 2,000 \text{ psi}$$

$$PN_2 = 1,561.6 \text{ psi}$$



# Dalton's Law

Expressed in atmospheres:

$$PN_2 = 2,000 \text{ psi} \times 1 \text{ atm}/14.7 \text{ psi} = 136.05 \text{ atm}$$

$$PN_2 = 0.7808 \times 136.05 \text{ atm}$$

$$PN_2 = 106.23 \text{ atm}$$



# Dalton's Law

- Why is Dalton's Law important to divers?



# Dalton's Law

- Why is Dalton's Law important to divers?
- A diver breathing from a tank containing a gas, or contaminate, which is easily tolerated at the surface may experience problems as the partial pressure increases with depth



# Henry's Law

- “The amount of any given gas that will dissolve in a liquid at a given temperature is proportional to the partial pressure of that gas in equilibrium with the liquid and the solubility coefficient of the gas in the particular liquid”



# Henry's Law

- In other words: If one unit of gas is dissolved at one atm, then two units will be dissolved at two atm, three at three atm, etc.





# Henry's Law

- Stated mathematically:

$$\frac{VG}{VL} = \infty P_1$$



# Henry's Law

- Where:
  - $V_G$  = Volume of gas dissolved at STPD (standard temperature pressure dry)
  - $V_L$  = Volume of the liquid
  - $\alpha$  = Solubility coefficient at specified temperatures
  - $P_1$  = Partial pressure of that gas above the liquid



# Henry's Law

- When a gas-free liquid is first exposed to a gas mixture, gas molecules will diffuse into the solution, pushed by the partial pressure of each individual gas



# Henry's Law

- As the gas molecules enter the liquid, they add to a state of “gas tension”
  - Gas tension is a way of identifying the partial pressure of the gas in the liquid



# Henry's Law

- The difference between the gas tension and the partial pressure outside the liquid is called the pressure gradient
  - This gives an indication of the net rate the gas tends to enter or leave the solution



# Henry's Law

- When the pressure gradient is high (low tension & high partial pressure), the rate of absorption into the liquid is high



# Henry's Law

- As the number of gas molecules in the liquid increases, the gas tension increases until it reaches equilibrium with the outside partial pressure
- At this point, the liquid is “saturated” with gas molecules, and the pressure gradient is zero



# Henry's Law

- Unless there is a change in temperature or pressure, the net rate at which gas molecules enter or leave a saturated liquid is zero





# Henry's Law

- How does Henry's Law apply to divers?



# Henry's Law

- How does Henry's Law apply to divers?
- The deeper one dives, the greater the pressure, the higher the total pressure of the breathing gas, and the more gas molecules are absorbed into tissues toward the equilibrium of saturation



# Henry's Law

- How does Henry's Law apply to divers?
- As the diver ascends, the pressure gradient reverses and the gas molecules begin to leave the diver's tissues



# Henry's Law

- How does Henry's Law apply to divers?
- If the diver's ascent rate is controlled properly, and all goes well, the excess gas molecules exit the diver's body via the lungs
- If not, gas bubbles may form, producing decompression sickness



# General Gas Law (Ideal Gas Law)

- The General Gas Law is a combination of Charles' and Boyle's laws
- It is used to predict the behavior of a given quantity of gas when changes may be expected in any or all of the variables (pressure, temperature, volume)



# General Gas Law

- Stated mathematically:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$



# General Gas Law

- Where:
  - $P_1$  = initial pressure (absolute)
  - $V_1$  = initial volume
  - $T_1$  = initial temperature (absolute)
  - $P_2$  = final pressure (absolute)
  - $V_2$  = final volume
  - $T_2$  = final temperature (absolute)



# General Gas Law

- An open-bottom diving bell of 24 ft<sup>3</sup> capacity is lowered to 99 fsw. The surface temperature is 80°F the temperature at depth is 45°F. What is the volume of the gas of the bell at depth?





# General Gas Law

- $P_1 = 14.7 \text{ psia}$
- $V_1 = 24 \text{ ft}^3$
- $T_1 = 80^\circ\text{F} + 460 = 540 \text{ Rankine}$
- $P_2 = 58.8 \text{ psia}$
- $T_2 = 45^\circ\text{F} + 460 = 505 \text{ Rankine}$
- $V_2 = \text{Unknown}$



# General Gas Law

$$V_2 = \frac{P_1 V_1 T_2}{T_1 P_2}$$



# General Gas Law

$$V_2 = \frac{(14.7 \text{ psia})(24 \text{ ft}^3)(505 \text{ R})}{(540 \text{ R})(58.8 \text{ psia})}$$



# General Gas Law

$$V_2 = 5.61 \text{ ft}^3$$



# Moisture In Breathing Gas

- Breathing gas should have sufficient moisture for comfort
  - Too much moisture can increase breathing resistance and produce lung congestion
  - Too little moisture can cause an uncomfortable sensation of dryness when breathed



# Moisture In Breathing Gas

- Gasses supplied from surface compressors or tanks can be assumed to be dry



# Humidity

- Water vapor (a gas) behaves in accordance with the gas laws; it condenses at temperatures we are likely to encounter while diving



# Humidity

- When water vapor condenses it can produce:
  - Condensation in the breathing hoses or mask
    - This can be a problem in very cold (freezing) conditions
  - Fogging of the mask
    - Can be prevented with saliva, liquid soap, or commercial anti-fogging products





# Light

- Eyes function by collecting light that is emitted or reflected by an object – objects that absorb light appear colored



# Light

- Water slows light - causing light to refract (bend) as it enters or leaves water. Light bends again when entering a mask. This creates distortion:
  - objects appear 25% larger
  - at distances of less than 4 feet, objects appear closer - at distances greater than 4 feet, objects appear farther



# Colors

- Color is absorbed by light according to its wavelength – the deeper the water, the more light is absorbed
  - Red is absorbed first, followed by orange, yellow, and green. In very deep water blue and violet may be the only colors visible
- Sunlight may penetrate to depths of 2000 ft



# Sound

- Sound is produced by pressure waves triggered by vibration
- The more dense the medium through which sound travels, the faster its speed
  - Speed of sound through air: 1,125 ft/second
  - Speed of sound through salt water: 5,023 ft/second
  - Speed of sound through steel: 16,600 ft/second
- Almost impossible to determine the direction from which sound originates underwater

