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)
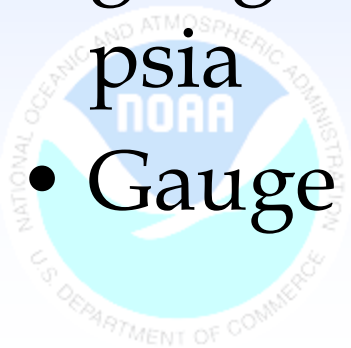
Gauge Pressure

- 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

- 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
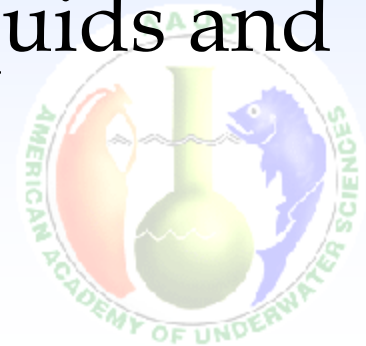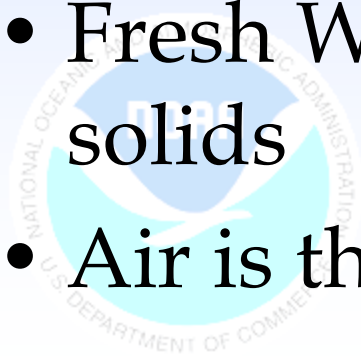
Density

- 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°F, and boils at 212°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 ft / 3.28 ft = 3.05 m
- Convert 10 meters to feet:
  - 10 m x 3.28 ft = 32.8 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^3) or cubic meters (m^3)

  - The English System, in addition to ft^3, uses other units of volume such as gallons

  - The SI uses the liter (L). One liter = 1000 cubic centimeters (cm^3) or 0.001 cubic meters (m^3), 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 lbs / 2.2 lbs = 81.8 kg

- Convert 82 kilograms to pounds:

  82 kg x 2.2 lbs = 180.4 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 (°F) scale or with the Celsius (centigrade) scale (°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 (°) 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:

$$°F + 460 = R$$

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:

$$°C + 273 = K$$

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_2)
- Nitrogen (N_2)
- Helium (He)
- Carbon Dioxide (CO_2)

- Carbon Monoxide (CO)
- Argon (Ar)
- Neon (Ne)
- Hydrogen (H_2)

Air

- Atmospheric Air is the most common gas breathed underwater

- It is composed of approximately:

  78% Nitrogen

  21% Oxygen

  1% other gases

Oxygen (O$_2$)

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

Oxygen (O$_2$)

- O$_2$ 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$_2$ available – better than nothing)

Nitrogen (N_2)

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

Nitrogen (N_2)

- As the partial pressure of N_2 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_2)

- CO_2 is a natural by-product of metabolism
- Excess carbon dioxide can cause unconsciousness that can be fatal in divers

Carbon Dioxide (CO$_2$)

- Elevated CO$_2$ 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$_2$)

- 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
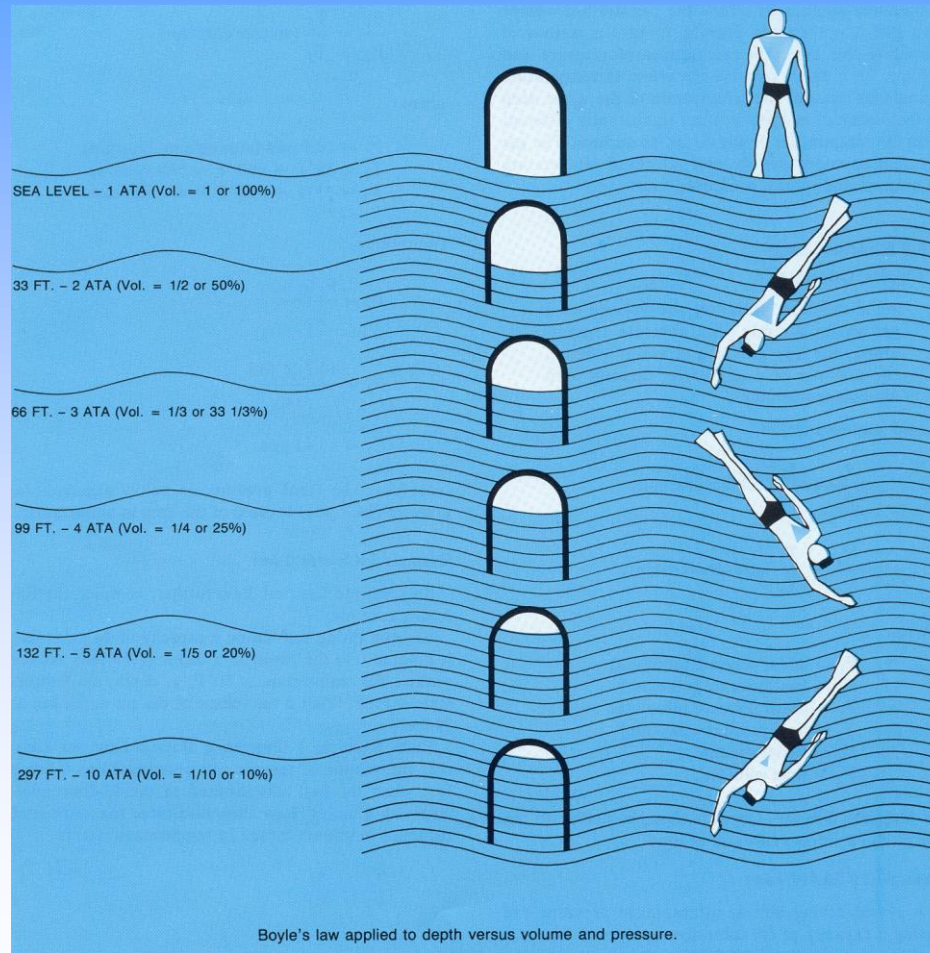
Boyle's Law

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

Boyle's Law Applied:

SEA LEVEL – 1 ATA (Vol. = 1 or 100%)

33 FT. – 2 ATA (Vol. = 1/2 or 50%)

66 FT. – 3 ATA (Vol. = 1/3 or 33 1/3%)

99 FT. – 4 ATA (Vol. = 1/4 or 25%)

132 FT. – 5 ATA (Vol. = 1/5 or 20%)

297 FT. – 10 ATA (Vol. = 1/10 or 10%)

Boyle's law applied to depth versus volume and pressure.

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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^3)
  - P_2 = final pressure absolute
  - V_2 = final volume in cubic feet (ft^3)

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 ft^3
  - P_2 = 33 fsw or 2 ata
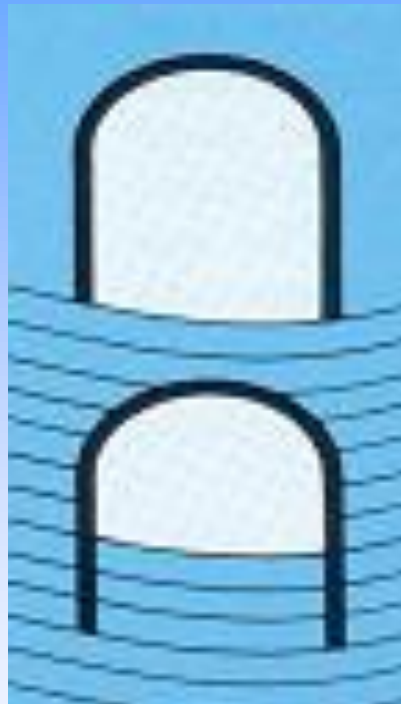 - V_2 = Unknown

Boyle's Law

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

Boyle's Law

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

Boyle's Law

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

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°F to 45°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: $V_1 / V_2 = T_2 / T_2$
  - V_1 = volume at 33 ft = 12 ft^3
  - T_1 = 80°F + 460 = 540 Rankine
  - T_2 = 45°F + 460 = 505 Rankine
  - V_2 = Unknown

Charles' Law - Volume Change

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

Charles' Law - Volume Change

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

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 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°F + 460 = 524 Rankine
- T_2 = 102°F + 460 = 562 Rankine
- P_2 = Unknown

Gay-Lussac's Law – Pressure Change

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

Gay-Lussac's Law – Pressure Change

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

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 psia – 14.7 psi = 3,218.6 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

- $P_t = PP_1 + PP_2 + PP_3$, etc.
  - P_t = Total Pressure
  - PP_1, 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:

$$P_x = Gas \ \% \ x \ P_t$$

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:

$$N_2 = 78.08\%$$

$$O_2 = 20.95\%$$

$$CO_2 = 0.03\%$$

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:

$$PN_2 = 0.7808 \text{ x } 1.0 \text{ atm}$$

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

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:

$PN_2 = 2,000$ psi x 1 atm/14.7 psi $= 136.05$ atm

$PN_2 = 0.7808$ x 136.05 atm

$PN_2 = 106.23$ atm

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:

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

Henry's Law

- Where:
  - VG = Volume of gas dissolved at STPD (standard temperature pressure dry)
  - VL = Volume of the liquid
  - $\propto$ = 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^3 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

- $P_1 = 14.7$ psia
- $V_1 = 24$ ft^3
- $T_1 = 80^o$F $+ 460 = 540$ Rankine
- $P_2 = 58.8$ psia
- $T_2 = 45^o$F $+ 460 = 505$ Rankine
- $V_2 =$ 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