PHYSICS OF DIVING - PRIMER

Humans typically operate within a fairly narrow atmospheric 'envelope' present at or near the earth's surface. The underwater environment is hostile and existence is dependent upon the ability to counteract the forces which can threaten human life. If divers are to operate safely, they must understand the characteristics of the subsea environment and the techniques required to manage its effects. An understanding of relevant physics is helpful in this regard.

This handout reviews the common physics that apply to diving. Computational examples include metric and US customary units. Quiz questions are provided at the end to support self-learning. The concepts should be reviewed prior to course participation.

Acronyms and Abbreviations

- ATA - atmospheres absolute (describing total atmospheric pressure)
- atm - atmosphere (describing partial pressure)
- DCS - decompression sickness
- fsw - feet of seawater
- ft - foot
- kPa - kilopascal
- m - meters; 1 m = 3.28084 ft
- msw - meters of seawater
- P_AO_2 - partial pressure of alveolar oxygen
- PCO_2 - partial pressure of carbon dioxide
- PN_2 - partial pressure of nitrogen
- PO_2 - partial pressure of oxygen
- psi - $lb \cdot in^{-2}$
- psia - $lb \cdot in^{-2}$ absolute (absolute pressure)
- psig - $lb \cdot in^{-2}$ gauge (gauge pressure)
- SEV - surface equivalent value

MATTER

Matter is anything that occupies space and has weight. It exists in three states:

Solid – has a definite shape, weight and volume, and is largely incompressible.

Liquid – has definite volume and weight, but no definite shape. Liquids take the shape of their containers and are practically incompressible.

Gas – has definite weight and occupies space, but lacks definite volume or shape, and is highly compressible.

The three states of matter (solids, liquids and gases) are affected by temperature and pressure.

ENERGY

The capacity to do work. There are six forms:

Mechanical – energy possessed by an object as a result of its position or condition.

> eg. when a body is held such that it can perform work when released, it possesses <u>potential</u> energy. When a body is moving, it possesses energy in motion or <u>kinetic</u> energy.

Heat – the energy possessed by a substance, as a result of the motion of its molecules. Heat added to a substance results in increased molecular speed and an associated rise in temperature.

Light – radiant light is energy in the form of electromagnetic radiation. Light energy from the sun provides the substance of green plants upon which all animal life depends on for food.

Chemical – energy stored within matter as a result of its molecular formation.
eg. coal, oil, and gas that release energy in the form of heat during combustion.

Electrical – energy associated with electrons (negative particles) or protons (positive particles).
eg. permanent magnets and storage batteries.

Nuclear – atomic energy is the force which holds the fundamental particles of the nucleus of atoms together. A nuclear power plant breaks down heavy nuclei into lighter nuclei (fission) with an associated controlled release of vast quantities of heat energy to generate steam.

Heat and Heat Transfer

- heat is an energy form closely related to temperature, but different objects can be heated to the same temperature and have different amounts of energy
- temperature is measured in either degrees Celsius (ºC) or degrees Fahrenheit (ºF)
- heat is measured in:
    - kilocalorie – heat energy required to raise the temperature of 1 kg of water by 1°C
    - calorie – heat energy required to raise the temperature of 1 mL of water by 1°C
    - BTU (British thermal unit) – heat energy required to raise the temperature of 1 lb of water by 1°F
- heat transfer is primarily accomplished through four avenues:
    - **conduction** – transmission of heat through materials in direct contact with each other (eg, cooking pot, diver in cool or cold water)
    - **convection** – transmission of heat by the movement of liquids or gases (eg, currents in air, currents in water)
    - **radiation** – transmission of heat by electromagnetic waves of energy; any relatively warm body radiates heat energy to any cooler body. Although a diver loses some heat by radiation, the amount is very small compared to losses due to conduction and convection
    - **evaporation** – energy cost of converting liquid, typically water in sweat, to a gas state

AIR

Air is a mixture of gases composed of:

Oxygen (O_2) – 21% by volume of air

- colorless, odorless, and tasteless
- readily combines with other gases
- matter cannot burn and life cannot be sustained without oxygen
- diving gas mixtures with an oxygen fraction ≤16% are considered hypoxic
- prolonged exposure to substantially elevated levels under pressure can be harmful

Nitrogen (N_2) – 78% by volume, it is the main constituent of air

- colorless, odorless and tasteless
- inert (chemically inactive) in the body
- enters and leaves the body as N_2
- incapable of supporting life
- narcotic effect on the body
    - becomes noticeable >3 atmospheres absolute (ATA)
    - referred to as 'nitrogen narcosis' or, historically, 'rapture of the deep'
    - individuals differ in their ability to manage the effects

Argon (Ar) – 0.9% by volume of air

- inert
- has been used experimentally with helium to reduce vocal distortion
- no advantage over helium due to greater density and greater narcotic potential than N_2

Carbon dioxide (CO_2) – 0.03% by volume of air

- colorless, odorless, and tasteless in low concentrations; sour, acidic taste at high concentrations
- chemically active
- stimulates the respiratory center of the brain
- CO_2 excess in inspired gas can impair cognition and be fatal

Rare gases – 0.02%

- helium (He), hydrogen (H_2), neon (Ne), krypton (Kr), xenon (Xe), radon (Rn), carbon monoxide (CO)
- argon is sometimes used in drysuits for its greater insulation value, but it is rarely worth the cost
- krypton and xenon have largely been rejected for diving

PRESSURE

Pressure is a force (weight) acting upon an area of matter.

- **force** is a push or pull, measured in kg or lb
- **area** is the surface area that the force is exerted upon

To calculate pressure, force or area:

Pressure = force per unit area: **P = F / A**

Expressed in kilopascals (kPa), atmospheres (atm); lb·in^{-2} (psi); bar; mm Hg, or cm of water

Example 1: What is the total force exerted on the inside of a hyperbaric chamber door when the door has an area of 720 in^2 and the chamber is pressurized to 27 psi (pounds per square inch)?

P = 27 psi   F = 27 * 720 = 19,440
F = ?
A = 720 in^2

Answer: The total force exerted on the chamber door is 19,440 lb.

Example 2: A scuba cylinder's internal walls have an area of 325 in^2. The total force exerted on this area is 512,700 lb. To what pressure is the cylinder charged?

P = ?   P = 512,700 ÷ 325 = 1,578 psi
F = 512,700 lb
A = 325 in^2

Answer: The scuba cylinder is charged to 1,578 psi.

Types of Pressure

Common units of pressure used in diving pounds per square inch (psi), atmospheres absolute (ATA), bar, and kilopascals (kPa). 1 pascal (Pa) = 1 N·m^{-2} or 1 kg·m^{-1}·s^{-2}. 1 bar = 100,000 Pa = 100 kPa. 1 ATA = 101.3 kPa = 14.7 psi.

Atmospheric pressure – the weight of the atmosphere produces a force on the surface of the earth. This pressure acts in all directions. The edge of the Earth's atmosphere (the boundary of space) is internationally recognized as an altitude of 100 km (62 miles), known as the Kármán line, where the pressure is close to 0 atmospheres absolute (ATA). Ambient pressure and gas density progressively increase closer to earth.

Absolute pressure – the total pressure being exerted. It is often expressed in pounds per square inch absolute (psia) or atmospheres absolute (ATA). At 5500 m (18,000 ft) the pressure is approximately 7.35 psi or 0.5 ATA. At sea level, the pressure that is exerted by the total weight of the atmosphere is 14.7 psi (1 ATA, 101.3 kPa, 760 mm Hg). ***Absolute pressure is used in discussion of the gas laws.***

Partial pressure – the fractional share of pressure exerted by a single gas in a mixture of gases. It is typically expressed in atmospheres (atm) or pounds per square inch (psi). An air mixture (21% oxygen) breathed at a depth of 66 fsw (20 msw/3 ATA) delivers a partial pressure of oxygen (PO_2) of 0.63 atm [0.21 * 3 ATA].

Gauge pressure – indicates the pressure in a closed structure that ignores the surrounding pressure. This is the case for pressure gauges that read zero when not pressurized. When a cylinder pressure gauge reads 1000 psi it means that the pressure is 1000 psi greater than the ambient (atmospheric) pressure. Gauge pressure in psi is written as psig.

Liquid pressure – the pressure exerted by the surrounding water at a given depth (ambient pressure). The pressure produced by a liquid is a function of its density. The density of saltwater is 64 lb per cubic foot (1.03 $g \cdot mL^{-1}$); the density of freshwater is 62.4 lb per cubic foot (1.00 $g \cdot mL^{-1}$). Water is practically incompressible, so its density remains virtually unchanged by depth.

- (US customary units) For every 1 ft of seawater (fsw), the pressure increases by 0.445 psi. Gauge pressure for any depth of seawater is determined by multiplying the depth in ft * 0.445.

  eg. What is the gauge pressure at 126 fsw?
  Answer: 126 * 0.445 = 56.1 psig

  (Metric units) For every 1 m of seawater (msw), the pressure increases by 10.13 kPa. Gauge pressure for any depth of seawater is determined by multiplying the depth in m * 10.13.

  eg. What is the gauge pressure at 38.4 msw?
  Answer: 38.4 * 10.13 = 380 kPa gauge

- (US customary units) If we have a pressure and want to know what depth in seawater this pressure is equal to, the pressure is divided by 0.445.

  eg. What depth in seawater is 33 psig equal to?
  Answer: 33 ÷ 0.445 = 74.2 fsw

  (Metric units) If we have a pressure and want to know what depth in seawater this pressure is equal to, the pressure is divided by 10.13.

  eg. What depth in seawater is 227.4 kPa gauge equal to?
  Answer: 227.4 ÷ 10.13 = 22.5 m

- (US customary units) For every foot of freshwater (ffw), the pressure is increased by 0.432 psi. To find the gauge pressure for any depth of freshwater, multiply the depth in ft * 0.432.

  eg. What is the gauge pressure at 87 ffw?
  Answer: 87 * 0.432 = 37.6 psig

- (US customary units) If we have a pressure and we want to know what depth in freshwater where this gauge pressure will be found, divide the pressure in ffw by 0.432.
  eg. What depth in freshwater is 36 psig equal to?
  Answer: 36 ÷ 0.432 = 83.3 ffw

- (US customary units) To convert a given pressure into atmospheres, divide the pressure by 14.7.
  eg. 3000 psig is equal to how many atmospheres?
  Answer: 3000 ÷ 14.7 = 204 atm gauge

Conversely, to convert atmosphere to psi, multiply atm * 14.7.

- (US customary units) To convert depth of seawater into atmospheres, divide the depth in ft by 33.
  eg. 165 fsw equals how many atmospheres?
  Answer: 165 ÷ 33 = 5 atm gauge

  Conversely, to convert atmospheres gauge to fsw, multiply the pressure in atm * 33.

- (Metric units) To convert depth of seawater into atmospheres, divide the depth in m by 10.
  eg. 50 msw equals how many atmospheres?
  Answer: 50 ÷ 10 = 5 atm gauge

  Conversely, to convert atmospheres gauge to msw, multiply the pressure in atm * 10.

- (US customary units) To convert freshwater depth into atmospheres, divide the depth in ft by 34.
  eg. 125 ffw equals how many atmospheres?
  Answer: 125 ÷ 34 = 3.7 atm gauge

  Conversely to convert atmospheres in ffw, multiply atm * 34.

- (Metric units) To convert depths of freshwater into atmospheres, divide the depth in m by 10.4.
  eg. 40 mfw equals how many atmospheres?
  Answer: 40 ÷ 10.4 = 3.8 atm gauge

  Conversely to convert atmospheres in ffw, multiply atm * 34.

Reminder: A*ll answers must be converted to absolute before using the gas law formulae*

DENSITY

Density is determined by the mass to volume ratio.
density = mass / volume

Water
Archimedes' principle - an object is buoyed up by the weight of the displaced water

freshwater: 1.00 $g \cdot mL^{-1}$ (62.4 $lb \cdot ft^{-3}$) - reference standard
saltwater: 1.03 $g \cdot mL^{-1}$ (64.0 $lb \cdot ft^{-3}$)

BUOYANCY

Archimedes' principle states, that ***'Any object wholly or partially immersed in a liquid is buoyed up by a force equal to the weight of the fluid displaced by the object.'***

The buoyant force of any liquid depends on its density or weight per unit volume.

Saltwater weighs 64 $lb \cdot ft^{-3}$, producing more buoyant force than freshwater which weighs 62.4 $lb \cdot ft^{-3}$. This is why ships sit lower in the water when proceeding from saltwater to freshwater environments.

Example 1: A block of cement 1 ft long x 2 ft wide x 2 ft high weighs 300 lb. If this block of cement was lowered into saltwater, how much would it weigh?

Step I: The volume (V=L * W * H) of the block is 1 * 2 * 2 = 4 ft^3

Step II: The block displaces 4 ft^3 of seawater, which means it is buoyed up by a force of 4 * 64 = 256 lb

Step III: The weight of the block when immersed in seawater would be 300 - 256 = 44 lb

The human body has a specific gravity of approximately 1.000. This is why most people have little difficulty floating in saltwater, which has a specific gravity of 1.025. The natural buoyancy of any diver can be temporarily increased by taking a deep breath of air. This inflates his chest, thus displacing water and increasing the upward buoyancy.

Flotation:

- A body which floats will displace a greater weight of liquid than its own weight if fully submerged. This is positive buoyancy.
- A body sinks when the weight of the liquid displaced is less than the weight of the body. This is negative buoyancy.
- A submerged body remains in equilibrium (neither floating nor sinking) when the weight of the liquid displaced equals the exact weight of the body. This is neutral buoyancy.

TEMPERATURE

The boiling and freezing points of water are key reference points in the two most common temperature scales used.

- **Fahrenheit** - water freezes at 32°F and boils at 212°F, with a range of 180 units.
- **Celsius** - water freezes at 0°C and boils at 100°C, with a range of 100 units.

To convert from °F to °C: °C = (°F-32) ÷ 1.8 eg. 60°F = (60 - 32) ÷ 1.8 = 28 ÷ 1.8 = 15.6°C

To convert from °C to °F: °F = (°C · 1.8) + 32 eg. 20°C = (20 · 1.8) + 32 = 36 + 32 = 68°F

Absolute temperature is used when making certain types of calculations, such as those of the ideal gas laws. Absolute zero is the lowest temperature that can be reached, that where all molecular motion would cease. This is -459.72ºF and -273.13ºC. These numbers are normally rounded to -460ºF and -273ºC.

To convert from Fahrenheit to absolute temperature (degrees Rankin: [ºR])
ºR = ºF + 460
To convert from Celsius to absolute temperature (degrees Kelvin [ºK])
ºK = ºC + 273

GAS LAWS

Gases are subject to three closely inter-related factors - temperature, pressure and volume. A change in any one of these factors will result in measurable change in one or more of the other factors.

A diver must know what effect changing pressures will have on his or her body and equipment during descent and ascent in the water column. Divers must be able to calculate air and mixed-gas supplies to determine if they are suitable to breathe and sufficient in volume at various depths.

Computations are calculated through the use of a set of rules, called gas laws.

Pressure must be converted to atmospheres absolute (ATA) for gas law computations.

Temperatures must be converted to absolute values for gas law computations.

Boyle's Law

'If temperature remains constant, the volume of a gas will vary inversely with the absolute pressure, while the density will vary directly with the absolute pressure.' For example, if the gas pressure in a flexible container is doubled the density is also doubled and the volume is decreased by one-half.

Pressure increase/Volume decrease can result in a drysuit squeeze if suit inflation is not used to compensate during descent.

Pressure decrease/Volume increase can result in a pulmonary overexpansion barotrauma if the pulmonary pressures cannot be controlled during ascent.

Density increases directly with the absolute pressure. If the absolute pressure on a gas is doubled, the density is doubled.

Boyle's law must be considered when dealing with pulmonary barotrauma, non-pulmonary barotrauma, gas supplies, or lift bags

Boyle's law, written in equation form is:

$$\mathbf{P_1V_1 = P_2V_2}$$

where: P_1 = initial pressure
V_1 = initial volume
P_2 = final pressure
V_2 = final volume

Example 1: A balloon is inflated on the surface at sea level with a volume of 3 ft^3 (85 L). If this balloon is taken down to 33 fsw (10 m), what would the volume of the balloon be?

$$\mathbf{P_1V_1 = P_2V_2}$$

where: P_1 = 1 ATA
V_1 = 3 ft^3
P_2 = 2 ATA
V_2 = ?

$$V_2 = \frac{P_1V_1}{P_2} = \frac{1 * 3}{2} = 1.5$$

Answer: The volume of the balloon at 33 ft (2 ATA) would be 1.5 ft^3.

$$\mathbf{P_1V_1 = P_2V_2}$$

where: P_1 = 1 ATA
V_1 = 85 L
P_2 = 2 ATA
V_2 = ?

$$V_2 = \frac{P_1V_1}{P_2} = \frac{1 * 85}{2} = 42.5$$

Answer: The volume of the balloon at 10 m (2 ATA) would be 42.5 L.

Example 2: A diver at 43 fsw (13 m) inspires to fill his lungs to approximately 6 L. If he were to ascend to the surface without exhaling what would the volume of air in his lungs be (assuming no rupture)?

$P_1V_1 = P_2V_2$

where: P_1 = 43 fsw ÷ 33 ft + 1 atm = 2.3 ATA

V_1 = 6 L

P_2 = 1 ATA

V_2 = ?

$$V_2 = \frac{P_1V_1}{P_2} = \frac{2.3 * 6}{1} = 13.8 \text{ L}$$

Answer: The volume of air in his lungs would be 13.8 L at the surface.

$P_1V_1 = P_2V_2$

where: P_1 = 13 m ÷ 10 m + 1 atm = 2.3 ATA

V_1= 6 L

P_2 = 1 ATA

V_2 = ?

$$V_2 = \frac{P_1V_1}{P_2} = \frac{2.3 * 6}{1} = 13.8 \text{ L}$$

Answer: The volume of air in his lungs would be 13.8 L at the surface.

Charles' Law

There are two parts. **Part I:** ***'if pressure is kept constant, the volume of a gas will vary directly with the absolute temperature.'*** **Part II:** ***'if volume is kept constant*** *(such as in scuba cylinders),* ***absolute pressure varies directly with the absolute temperature.'***

Charles' law impacts:

- charging of air or mixed gas cylinders
- recompression chamber operations
- inflation of Zodiac pontoons

The two parts of Charles' law written in equation form are:

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

Example 1: A Zodiac's pontoons are partially inflated to a volume of 7 ft^3 in an air temperature of 47°F (8°C). What will the volume of the pontoons be if the boat is warmed to 75°F (24°C)?

Step I: $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

where: V_1 = 7 ft^3

T_1 = 47°F + 460 = 507°R

V_2 = ?

T_2 = 75°F + 460 = 535°R

Step II: $V_2 = \frac{V_1T_2}{T_1} = \frac{7 * 535}{507} = 7.39 \text{ ft}^3$

Answer: The volume would increase to 7.4 ft^3 due to the temperature rise.

Step I: $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

where: V_1 = 198 L

T_1 = 8°C + 273 = 281°K

V_2 = ?

T_2 = 24°C + 273 = 297°K

Step II: $V_2 = \frac{V_1T_2}{T_1} = \frac{198 * 297}{281} = 209 \text{ L}$

Answer: The volume would increase to 209 L due to the temperature rise.

Example 2: A scuba tank filled to 2250 psig (155 bar) is stored in a room where the temperature is 27°C. What will the cylinder be when the tank is put into water (and stabilized) with a temperature of 2°C?

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

where: P_1 = 2250 ÷ 14.7 + 1 atm = 154.1 ATA

T_1 = 27°C + 273 = 300°K

P_2 = ?

T_2 = 2°C + 273 = 275°K

$$P_2 = \frac{P_1 T_2}{T_1} = \frac{154.1 * 275}{300} = 141.2 \text{ ATA}$$

141.2 ATA - 1 = 140.2 atm gauge

140.2 * 14.7 = 2061.3 psig

Answer: The pressure in the cylinder would decrease ~8% to 2061 psig.

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

where: P_1 = 155 bar ÷ 1.013 + 1 atm = 154 ATA

T_1 = 27°C + 273 = 300°K

P_2 = ?

T_2 = 2°C + 273 = 275°K

$$P_2 = \frac{P_1 T_2}{T_1} = \frac{154 * 275}{300} = 141.2 \text{ ATA}$$

141.2 ATA - 1 = 140.2 atm gauge

140.2 * 1.013 = 142 bar gauge

Answer: The pressure in the cylinder would decrease ~8% to 142 bar.

General Gas Law

Boyle and Charles demonstrated that with a gas – any gas – the factors of temperature, pressure, and volume were so interrelated that a change in anyone of these factors must be balanced by a corresponding change in one or both of the others. Boyle's law deals with pressure/volume relationships and Charles' law deals with the effect of temperature changes on pressure and/or volume.

The general gas law is a convenient combination of these two laws in predicting the behavior of a given quantity of gas when changes may be expected in any or all of the variables.

The general gas law, written in equation form is:

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

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)

When working with this formula, a few simple rules must be kept in mind:

- there can only be one unknown
- if it is known that a value remains unchanged (such as volume in an air tank) or that the change in one of the variables will be of little consequence, the values on both sides can be cancelled to simplify the equation.
- all values must be changed to absolute for computation

Sample problems using the general gas law:

Example 1: You have an inflated lift bag on the surface. The volume of the bag is 5 ft^3 (142 L) and the surface water temperature is 78°F (26ºC). If the lift bag is taken down to 66 fsw (20 msw) where the water temperature is 43°F (6ºC), what will the volume of the lift bag be?

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

where: P_1 = 1 ATA
V_1 = 5 ft^3
T_1 = 78°F + 460 = 538°R
P_2 = 66 ÷ 33 + 1 = 3 ATA
V_2 = ?
T_2 = 43°F + 460 = 503°R

$$V_2 = \frac{P_1V_1T_2}{T_1P_2} = \frac{1 * 5 * 503}{538 * 3} = 1.55\ ft^3$$

Answer: The lift bag volume would be reduced to 1.55 ft^3.

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

where: P_1 = 1 ATA
V_1 = 142 L
T_1 = 26°C + 273 = 299°K
P_2 = 20 ÷ 10 + 1 = 3 ATA
V_2 = ?
T_2 = 6°C + 273 = 279°K

$$V_2 = \frac{P_1V_1T_2}{T_1P_2} = \frac{1 * 142 * 279}{299 * 3} = 44.2\ L$$

Answer: The lift bag volume would be reduced to 44 L.

Example 2: An air compressor on the surface with an ambient temperature of 28°C (82ºF) has a volume output of 4250 L/min (150 ft^3/min). Disregarding line loss, what gas volume would be supplied to a diver at 26 msw (85 fsw) with a water temperature of 4°C (39ºF)?

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

where: P_1 = 1 ATA
V_1 = 4250 L
T_1 = 28°C + 273 = 301°K
P_2 = 26 ÷ 10 msw + 1 atm = 3.6 ATA
V_2 = ?
T_2 = 4°C + 273 = 277°K

$$V_2 = \frac{P_1V_1T_2}{T_1P_2} = \frac{1 * 4250 * 277}{301 * 3.6} = 1086\ L$$

Answer: The volume supplied by the compressor to 26 msw would be reduced to 1086 L/min.

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

where: P_1 = 1 ATA
V_1 = 150 ft^3
T_1 = 82°F + 460 = 542°R
P_2 = 85 ÷ 33 fsw + 1 atm = 3.6 ATA
V_2 = ?
T_2 = 39°F + 460 = 499°R

$$V_2 = \frac{P_1V_1T_2}{T_1P_2} = \frac{1*150*499}{542 * 3.6} = 38.4\ ft^3/min$$

Answer: The volume supplied by the compressor at 85 fsw would be 38 ft^3/min.

Dalton's Law

When a mixture of gases is confined in a container, they exert a total pressure. The total pressure is equal to the sum of all individual pressure exerted by each gas present in the mixture. Dalton's law states, ***'The total pressure exerted by a mixture of gases is the sum of the pressures that would be exerted by each individual gas if it alone was present and occupied the total volume.'***

$$P_{total} = P_1 + P_2 + P_3 + ...$$

The pressure contributed by any gas in a mixture is proportional to the number of molecules in that gas in the total volume – and the pressure of that gas is called it's partial pressure, meaning it's part of the whole. For example, the air we breathe contains approximately 21% oxygen and 78% nitrogen. At sea level the absolute atmospheric pressure is 14.7 psi or 1 ATA; the PO_2 would be 0.21 atm and the PN_2 0.78 atm.

To find the actual pressures, simply multiply:

O_2:	0.21 * 14.7 = 3.1 psi
N_2:	0.78 * 14.7 = 11.5 psi
misc:	0.01 * 14.7 = 0.1 psi
Total pressure:	14.7 psi

A more convenient way of working with partial pressures is with atmospheres. In the previous example, percentages of gases were converted into psi at sea level. Using absolute atmospheres (ATA) to find the partial pressure that oxygen and nitrogen each exert, simply multiply:

O_2:	0.21 * 1 ATA = 0.21 atm	O_2:	0.32 * 1 ATA = 0.32 atm
N_2:	0.78 * 1 ATA = 0.78 atm	N_2:	0.67 * 1 ATA = 0.67 atm
misc.:	0.01 * 1 ATA = 0.01 atm	misc.:	0.01 * 1 ATA = 0.01 atm
Total pressure:	1.00 ATA	Total pressure:	1.00 ATA

Note: the miscellaneous gas fraction is often ignored in practical gas calculations.

The partial pressure of a gas at any depth can be computed by multiplying the percentage of that gas by the absolute pressure at the target depth (eg, in psi or ATA).

Example 1: What are the partial pressures of O_2 and He (in atm) for a 16/84 mix at a depth of 132 fsw?

Step I: 132 fsw ÷ 33 fsw + 1 atm = 5 ATA

Step II: PO_2 = 5 * 0.16 = 0.8 atm
P_{He} = 5 * 0.84 = 4.2 atm

This can also be calculated using metric units (eg. meters of seawater), where 132 fsw = 40 msw, and 33 fsw = 10 msw.

Step I: 40 msw ÷ 10 msw + 1 atm = 5 ATA

Step II: PO_2 = 5 * 0.16 = 0.8 atm
P_{He} = 5 * 0.84 = 4.2 atm

Example 2: What is the partial pressure of each gas in psia for 40/60 O_2/N_2 nitrox mix when breathed at a depth of 35 msw (115 fsw)?

Step I: (35 ÷ 10 + 1) * 14.7 = 66.15 psia
or
Step I: 35 * 1.47 + 14.7 = 66.15 psia

Step II: PO_2 = 0.40 * 66.15 = 26.5 psia
PN_2 = 0.60 * 66.15 = 39.7 psia

Step I: (115 ÷ 33 + 1) * 14.7 = 65.9 psia
or
Step I: 115 * 0.445 + 14.7 = 65.9 psia

Step II: PO_2 = 0.40 * 65.9 = 26.4 psia
PN_2 = 0.60 * 65.9 = 39.5 psia

As a diver descends in the water column and the pressure of the air breathed increases, so do the number of molecules inspired. The partial pressure of O_2 (PO_2) breathed is managed to reduce the risk of central nervous system oxygen toxicity (important since a seizure occurring underwater will often not be survivable). Commercial diving standards now limit the maximum PO_2 to 1.4 atm during the working phase of a dive, and to 1.6 atm for the final, resting decompression phase of dives. Recreational diving standards limit the maximum PO_2 to 1.4 atm.

Henry's Law

When a liquid is exposed to a gas, molecules of the gas will diffuse into the liquid. The process is much like that of gases diffusing through a membrane, but here the point of equilibrium is influenced by the solubility of the gas in the liquid. The solubility rates of gases and liquids vary depending on the type of liquids and gases (for example, N_2 is five times more soluble in fat than water). There are two physical conditions which have a great effect upon the quantity of gas which will be absorbed by a liquid though; these are temperature and pressure. Since a diver is exposed to unusual pressures, an understanding of how pressure affects gas absorption is particularly important.

Henry's law states, ***'The amount of gas that will dissolve in a liquid at a given temperature is almost directly proportional to the partial pressure of that gas'.***

If one unit of gas is dissolved at one atmosphere, then two will be dissolved at two atmospheres, three units at three atmospheres, etc.

As molecules of gas enter a liquid, they add to a state of gas tension, which is a way of identifying the partial pressure of that gas in a liquid.

The difference between the gas tension in the liquid and the partial pressure outside the liquid is called the pressure gradient. When the gradient is high, with low tension and high partial pressure, the rate of absorption into the liquid is high.

When the gas tension in the liquid and the partial pressure of the gas outside the liquid are equal, the liquid is said to be saturated.

Temperature affects the solubility of gas in liquids – the lower the temperature, the higher the solubility. The bubbles of gas that rise from a pan of water long before it boils are bubbles of dissolved gas coming out of solution.

Henry's Law and Decompression

The gases in a diver's breathing mixture will dissolve into their tissues in proportion to the partial pressure of each gas in the mixture. Because of the varied solubility and diffusion rates of different gases, the quantity which dissolves will also be governed by the length of time the diver is breathing the gas at increased pressure.

Oxygen is metabolized by the body while inert gases such as N_2 and He are not. If a diver breathes a gas mixture under pressure long enough, inert gases accumulate in his tissues until a state of saturation is reached; at this point, no further gas can be absorbed by the tissues at that depth. Depending on the gas, saturation may be reached within 12 to 24 hours.

Whatever the quantity of an inert gas that has been dissolved in the diver's tissues, it will remain in solution as long as the pressure is maintained.

When the diver starts to ascend toward the surface, more and more of the dissolved gas will come out of solution.

If the rate of ascent is controlled appropriately, the dissolved gas will be effectively delivered to the lungs and exhaled before it accumulates enough to form bubbles in the tissues. However, if the diver ascends faster than the body can accommodate, bubbles may form in a variety of tissues, creating a risk for decompression sickness (DCS).

SURFACE EQUIVALENT VALUE

Surface equivalent value (SEV) provides the exposure concentration at the surface that equates to that of a given gas breathed at depth; this is effectively matching the number of molecules the diver is breathing.

For example, a diver breathing air on the surface contaminated with 2% carbon monoxide (CO) would likely not be adversely affected (CO partial pressure of 0.02 atm). However, if the diver descended to 132 fsw (40 msw, 5 ATA) the same gas would yield a CO partial pressure of 5 * 0.02 = 0.1 atm. This would be equal to breathing 10% CO on the surface, a dangerously high level.

PERCEPTION OF LIGHT AND SOUND UNDERWATER

Light is part of the electromagnetic spectrum that is visible to the unaided eye. The effects of light underwater consist principally of four major changes in a diver's ability to perceive objects.

- **diffusion** – in water, light rays are scattered in all directions by suspended particulate matter and dissolved matter. This reduces illumination.
- **refraction** – bends the light rays making objects appear closer and larger.
- **turbidity** – blocks light. This is caused by suspended material such as algae, fine sediment, or pollutants in the water. The greater the level of turbidity, the greater the vision loss will be. Even though vision may be blocked light can still be present.
- **absorption** – light is absorbed by water, starting with the longest wavelengths. The order of absorptions is red, orange, yellow, green, blue, indigo, and violet. Divers will be able to perceive only the shortwave colors at depth unless using lights to restore the visible spectrum.

Sound travels ~4.5-times faster in water than in air.

- sound travels at 335 m/s (1100 ft/s) in air vs. 1508 m/s in water (4900 ft/s)
- its speed is greatly reduced when passing from one medium to another
- it is more difficult to localize the source of sound heard underwater since there is less differential in the time taken to reach the two ears
- when using He instead of N_2 as the inert gas component of a diver's breathing gas (heliox), vocal quality is more pronouncedly altered to produce a 'Donald Duck' effect in a diver's speech. Sound travels through helium faster than air, so as He molecules travel past the vocal cords, the increased speed with which the sound travels increases the pitch of a diver's voice.

REVIEW QUIZ

1. Briefly define matter.

2. List the three states in which matter exists.

3. Briefly define energy.

4. List the forms or types of energy.

5. Name four ways heat is transferred.

6. Convert 28°C to °F.

7. Convert 76°F to °C.

8. List the principal components of dry air and their percentages.

9. List the 2 most common units used to state pressure in the diving environment.

10. What is the atmospheric pressure at sea level (in two different units)?

11. What is the gauge pressure in psi at each of the following depths?
    a. 37 fsw
    b. 43 ffw
    c. 168 fsw
    d. 210 fsw
    e. 83 ffw

12. What are the depths in saltwater that are equivalent to the following gauge pressures? (answer in fsw)
    a. 53 psig
    b. 25 psig
    c. 115 psig
    d. 8 psig
    e. 41 psig

13. Convert the following pressures to atmospheres absolute.
    a. 3000 psig
    b. 2250 psig
    c. 1800 psig
    d. 500 psig
    e. 300 psig

14. What does one cubic foot (ft^3) of saltwater weigh?

15. What does a cubic foot (ft^3) of freshwater weigh?

16. What is the absolute pressure in atmospheres at 107 fsw?

17. An absolute pressure of 9.7 atmospheres absolute (ATA) is found at what depth of seawater?

18. State three types of pressure.

19. State Boyle's law.

20. Write Boyle's law in equation form.

21. An air-filled float has a volume of 3.7 ft^3 at the surface. What will the volume be if it was taken to 87 fsw (26.5 msw) without adding or removing any air?

22. A sealed balloon containing 4 ft^3 of air at 63 fsw is released and rapidly ascends to the surface. What volume of air would it contain at the surface?

23. An open bottom diving bell has an internal volume of 12 ft^3 at the surface. What would the gas volume be if it was lowered to 87 fsw (26.5 msw) with no gas added ?

24. State the two parts of Charles' law.

25. Write the two parts of Charles' law in equation form.

26. What must you add to temperature in Fahrenheit to convert it to absolute temperature?

27. What must you add to temperature in Celsius to convert it to absolute temperature?

28. A set of aqualung cylinders are charged to 3000 psig and are lying in the shade where the temperature is 55°F. They are moved out into the sun where the temp is 87°F. What will the pressure inside the tanks eventually become? (answer in psig)

29. A zodiac's pontoons are partially inflated with air. They have a volume of 12 ft^3 and the temperature is 43°F. If the temp rises to 75°F, what will the volume of air become?

30. The general gas law is the combination of what two laws?

31. State the general gas law in equation form.

32. An air compressor delivers 35 ft^3/min at the surface where the temp 75°F. Disregarding line loss, what will the compressor put out at 73 fsw where the temp is 45°F.

33. A diver wearing a Superlite 27 helmet is at a depth of 140 fsw and the temp is 48°F. He requires 2 ft^3/min of air at depth. If the surface temp is 85°F, how much would an air compressor have to put out in order to deliver 2 ft^3/min to the diver?

34. State Dalton's law.

35. What is the maximum partial pressure of oxygen allowed for the working phase of commercial diving operations according to the Canadian Standards Association guidance?

36. Gas mixture 80% N_2 20% O_2. What is the partial pressure in atmospheres of each gas at a depth of 180 fsw (55 msw)?

37. What is the partial pressure in psi of each gas of a 40% O_2, 30% N_2 and 30% He gas mix at 154 fsw (47 msw)?

38. You have an air supply that is contaminated with 3% carbon monoxide (CO). If a diver breathes this air at 145 fsw (44 msw), what would the surface equivalent value (SEV) be in percent of CO?

39. State Henry's law.

40. What does saturation mean when referring to gases and liquids?

41. What is a pressure gradient?

42. A diver at the surface has approximately 1 L of nitrogen dissolved in his body. How much nitrogen would be dissolved in his body tissues if he were saturated at a depth of 175 fsw (53 msw)?

43. State Archimedes principle.

44. An object displaces 3.7 ft^3. How much force is it buoyed up by in freshwater?

45. An object is 16 inches long x 10 inches high x 15 inches wide, and weighs 63 lb in air. If this object is placed in saltwater will it sink or float? How much positive or negative buoyant will it be? (one ft^3 = 1728 in^3; area of a cube = L x W x H).

46. A cement clump with dimensions of 4 ft x 5 ft x 3 ft weighs 12,071 lb in air. How much will this clump weigh when it is submerged to 105 fsw (32 msw)?

47. An object on the bottom of the ocean weighs 293 lb (133 kg). What is the minimum volume lift bag that would be required to raise this object off the bottom? (answer in ft^3)

48. List four things which can cause changes to light underwater.

49. How fast does sound travel underwater compared to travel in air?

50. Why does a diver have difficulty knowing which direction sound is coming from underwater?

ANSWERS TO REVIEW QUIZ

1. Matter is anything that has weight and occupies space.

2. solid, liquid, gas

3. Energy is the capacity to do work.

4. electrical, chemical, mechanical, radiant, nuclear, heat

5. conduction, convection and radiation.

6. 82.4°F

7. 24.4°C

8. Air composition
   nitrogen: 78.1%
   oxygen: 20.9%
   argon 0.93%
   carbon dioxide 0.03%
   rare gases 0.02%

9. pounds per square inch (psi) and atmospheres absolute (ATA)

10. 14.7 psia or 1 ATA

11. 16.46 psi; 18.61 psi; 74.76 psi; 93.45 psi; 35.93 psi

12. 119.1 fsw; 56.2 fsw; 258.4 fsw; 17.9 fsw; 92.1 fsw

13. 205.1 ATA; 154.1 ATA; 123.4 ATA; 35.0 ATA; 21.4 ATA

14. 64 lb

15. 62.4 lb

16. 4.24 ATA

17. 287 fsw

18. atmospheric, gauge, absolute

19. The volume of a gas is inversely proportional to the absolute pressure, while the density of a gas is directly proportional to the absolute pressure.

20. $P_1 V_1 = P_2 V_2$

21. 1.02 ft^3

22. 11.6 ft^3

23. 3.3 ft^3

24. a) if pressure is constant, the volume of a gas will vary directly with the absolute temperature
b) if volume is constant, absolute pressure varies directly with the absolute temperature

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

26. add 460 deg

27. add 273 deg

28. 3187 psig

29. 12.8 ft^3

30. Charles' and Boyle's laws

31. $\frac{P_1V_1}{T_1}$ $\frac{P_2V_2}{T_2}$

32. 10.29 ft^3/min.

33. 11.24 ft^3/min.

34. The total pressure exerted by a mixture of gases is the sum of the pressures that would be exerted by each gas if it alone were present and occupied the total volume.

35. 1.3 atm

36. N_2 = 5.16 atm; O_2 = 1.29 atm

37. O_2 = 33.29 psia; N_2 = 24.96 psia; He = 24.96 psia

38. 16%

39. The amount of gas that will dissolve in a liquid is almost directly proportional to the partial pressure of that gas.

40. When the gas tension in the liquid equals the partial pressure, the liquid is said to be saturated.

41. The difference between the gas tension in the liquid and the partial pressure of the gas.

42. 6.3 L

43. Any object wholly or partially immersed in a liquid is buoyed up by a force equal to the amount of liquid displaced by the object.

44. 230.9 lb

45. 26.0 lb positive buoyancy

46. 8231 lb negative buoyancy

47. A 4.58 ft^3 lift bag is required

48. diffusion, refraction, turbidity, absorption.

49. Approximately 4.5-times faster

50. Sound traveling underwater reaches both ears at approximately the same time.