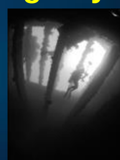
Diving Physics



Topics in this Chapter

- ✓ Introduction
- ✓ Principles of Pressure
- ✓ Properties of Water
- ✓ Temperature
- ✓ Archimedes' Principle
- ✓ Boyle's Law
- ✓ Charles' Law & Guy-Lussac's Law
- ✓ Combined & Ideal Gas Laws
- ✓ Dalton's Law
- ✓ Henry's Law
- ✓ Light
- ✓ Sound
- ✓ Haldane's Decompression Model

Introduction

- **The Laws of Physics**
  - These principles are equally applicable above and below the surface
    - **Changes occur more quickly underwater, and the effects can be dramatic**

Principles of Pressure

- **Pressure**
  - The force, or weight, pressing upon a surface
    - Units of measurement
      - 1 bar = 1 kilogram per square centimetre
      - 1 atm = 14.7 pounds per square inch
      - 1 bar = 1 atm

Principles of Pressure

- **Ambient Pressure**
  - The absolute or total pressure
    - Includes the weight of the overhead atmosphere plus the weight of the overhead water
      - Atmosphere = 1 bar or 1 atm
      - 10 metres of seawater = 1 bar
      - 33 feet of seawater = 1 atm

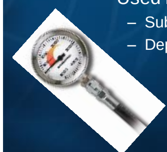
Principles of Pressure

- **Ambient Pressure**

Depth in Seawater		Ambient Pressure
0 m	0 ft	1 bar / atm
10 m	33 ft	2 bar / atm
20 m	66 ft	3 bar / atm
30 m	99 ft	4 bar / atm
40 m	132 ft	5 bar / atm
50 m	165 ft	6 bar / atm

Principles of Pressure

- **Gauge Pressure**
  - Effectively disregards atmospheric pressure, and only indicates the force exerted by another source of pressure
    - Used in two types of dive instruments
      - Submersible pressure gauge
      - Depth gauge



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Principles of Pressure

- **Pressure Calculations**
  - For different types of SPG readings

Imperial-to-Metric

bar = psi / 14.7

Metric-to-Imperial

psi = bar x 14.7

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Principles of Pressure

- **Pressure Calculations**

Imperial (Known Depth)

P = [D / 33] + 1 *or* P = [D + 33] / 33

Imperial (Known Pressure)

D = [P – 1] x 33 *or* D = [P x 33] – 33

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Principles of Pressure

- **Freshwater versus Saltwater**
  - Freshwater weighs less than saltwater, and freshwater water exerts less pressure than saltwater
    - 1 bar = 10 metres of saltwater
    - 1 bar = 10.3 metres of freshwater
    - 1 atm = 33 feet of saltwater
    - 1 atm = 34 feet of freshwater

Principles of Pressure

- **Freshwater versus Saltwater**
  - Most depth gauges and personal dive computers are calibrated for saltwater

Principles of Pressure

- **Pressure Calculations**
  - To covert *freshwater* depth to pressure

Imperial

P = [D / 34] + 1 *or* P = [D + 34] / 34

- To covert pressure to *freshwater* depth

Imperial

D = [P – 1] x 34 *or* D = [P x 34] – 34

Principles of Pressure

- **Pressure Calculations**
  - To determine actual *freshwater* depth, from depth gauge

Imperial

feet of freshwater = feet of saltwater x 1.03

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Physical Properties of Water

- **Density of Water**
  - 800x denser than air
    - Greater resistance while moving underwater
      - Diver should streamline himself and his equipment
      - Diver should move slowly and steadily to avoid over-exertion

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Thermal Properties

- **Thermal Conductivity of Water**
  - Water conducts heat more efficiently than air
    - Whisks away body heat 25x faster
    - Without proper exposure protection a diver will become chilled, over time, even in relatively warm water

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Properties of Light

- **Refraction of Light in Water**
  - Light rays refract (bend) when passing from one medium to another of different densities
    - The human eye is designed to focus light entering from the air
      - The dive mask restores normal vision by adding an air space in front of the eyes
    - As light rays pass from water to the air space of the mask, it creates a magnifying effect
      - Objects appear 33% larger and 25% closer

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Properties of Light

- **Diffraction of Light in Water**
  - Light rays normally travel in a straight line
    - Suspended particles in water can deflect the rays and cause a random divergence of light
      - An object may appear to be closer than it actually is (visual reversal)

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Properties of Light

- **Color Loss in Water**
  - The perception of color depends upon the visible wavelengths of light emitted or reflected by an object
    - Visible spectrum – "Roy G Biv"
      - ❑ Red — *Longest Wavelength*
      - ❑ Orange
      - ❑ Yellow
      - ❑ Green
      - ❑ Blue
      - ❑ Indigo
      - ❑ Violet — *Shortest Wavelength*

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Properties of Light

- **Color Loss in Water**
  - Wavelengths of light are absorbed as they travel through water, and the extent of color loss depends upon distance
    - Distance (depth) that sunlight passes through water to illuminate an object
    - Distance that emitted or reflected light, from an object, passes through water before reaching a diver's eyes

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Properties of Light

- **Color Loss in Water**
  - The longest wavelengths are the first to be absorbed
    - Red disappears fairly quickly
    - Eventually everything turns to shades of grey
    - Water also may add its own tint, depending upon nutrients present in the water
      - Tropical saltwater tends to be blue
      - Temperate saltwater tends to be green
      - Freshwater might be green or brown

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Properties of Light

- **Color Loss in Water**
  - Natural colors can be restored with a nearby artificial source of light
    - Dive light
    - Photo flash (strobe)

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Properties of Sound

- **Transmission of Sound in Water**
  - Sound waves travel faster and farther through a denser medium
    - About 4x faster in water than air
    - Increased speed makes it difficult to determine the direction of sound underwater

Properties of Sound

- **Transmission of Sound in Water**
  - Other factors affecting the movement of sound waves through water
    - Pressure
    - Temperature
    - Salinity

Properties of Sound

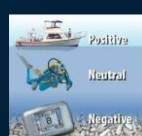
- **Transmission of Sound in Water**
  - Unlike light, sound waves do not easily pass from one medium to another of different densities
    - Underwater sounds usually cannot be heard above water
    - Above water sounds usually cannot be heard underwater
    - Sound waves can be reflected and dissipated by a thermocline or halocline

Archimedes' Principle

- **Buoyancy**
  - When immersed in a fluid, an object will experience a buoyant force equal to the weight of the displaced fluid

Archimedes' Principle

- **Buoyancy**
  - States of buoyancy
    - Positive: object is lighter than the displaced fluid (the object floats)
    - Negative: object is heavier than the displaced fluid (the object sinks)
    - Neutral: object weighs the same as the displaced fluid (the object hovers in mid-water)



Archimedes' Principle

- **Buoyancy**
  - There are degrees of positive and negative buoyancy, but neutral buoyancy is an exact point

Archimedes' Principle

- **How this Principle Relates to Diving**
  - It explains why certain objects float, while others sink
    - It also suggests that buoyancy characteristics can be adjusted by . . .
      - Changing the weight of an object
      - Changing the volume of fluid which is displaced by an object

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Archimedes' Principle

- **How this Principle Relates to Diving**
  - Items used by a diver to control buoyancy
    - BCD
      - Inflation and deflation alters the volume of water which is displaced
    - Lead weights
      - To offset the overall positive buoyancy of a diver and his equipment
    - Lung volume
      - Fine tune buoyancy on a temporary basis

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Archimedes' Principle

- **Saltwater versus Freshwater**
  - Saltwater weighs more than freshwater, so an object will be more buoyant in saltwater that freshwater
    - Saltwater
      - 1 litre = 1.03 kilograms
      - 1 cubic foot = 64 pounds
    - Freshwater
      - 1 litre = 1 kilogram
      - 1 cubic foot = 62.4 pounds

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Archimedes' Principle

- **Buoyancy Calculations**
  - To determine the buoyancy of an object

Imperial

buoyancy = weight of object – [(cu ft displaced) x (lbs per cu ft of water)]

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Archimedes' Principle

- **Buoyancy Calculations**
  - To achieve neutral buoyancy

Imperial

cu ft required = [lbs of negative buoyancy] / [lbs per cu ft of water]

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Boyle's Law

- **Pressure and Volume**
  - Any change in pressure, applied upon a gas in a flexible container, will result in a corresponding and inversely proportional change in volume
    - Though not part of the original principle, in practice Boyle's Law has been expanded to also include the density of the gas

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Boyle's Law

- **Pressure and Volume**

Depth in Seawater		Ambient Pressure	Volume	Density
0 m	0 ft	1 bar / atm	x 1	x 1
10 m	33 ft	2 bar / atm	x 1/2	x 2
20 m	66 ft	3 bar / atm	x 1/3	x 3
30 m	99 ft	4 bar / atm	x 1/4	x 4
40 m	132 ft	5 bar / atm	x 1/5	x 5
50 m	165 ft	6 bar / atm	x 1/6	x 6

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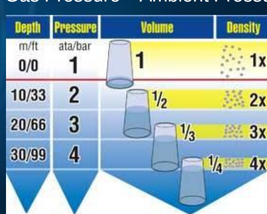
Boyle's Law

- **Pressure and Volume**
  - Inside a flexible container

Gas Pressure = Ambient Pressure



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Boyle's Law

- **How this Principle Relates to Diving**
  - Equalization
    - The middle ears and nasal sinuses must be equalized during descent (to avoid a squeeze) and during ascent (to avoid a reverse block)

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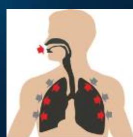
Boyle's Law

- **How this Principle Relates to Diving**
  - Equalization
    - The lungs are equalized to changing ambient pressure through normal respiration (a diver should never hold his breath while underwater)



Boyle's Law

- **How this Principle Relates to Diving**
  - Air consumption
    - It takes more molecules of air, drawn from the scuba cylinder with each inhaled breath, to fill a diver's lungs at depth
      - A cylinder full of air, which lasts one hour at the surface, will last only 15 minutes at 30 m / 99 ft

Boyle's Law

- **How this Principle Relates to Diving**
  - Breathing effort
    - The density of air, inhaled by a diver, increases with depth
      - Normally it is unnoticed by the diver, when a proper pattern of breathing is maintained
      - Over-exertion increases the breathing rate and turbulence may occur in the airway

Boyle's Law

- **How this Principle Relates to Diving**
  - Buoyancy
    - Air, within the BCD, compresses as a diver descends and expands as a diver ascends, in response to changing ambient pressure
      - Any change in depth will require an adjustment in buoyancy control
    - Similarly the air inside a dry suit, and the neoprene material of a wet suit, also compress and expand in response to changing ambient pressure

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Boyle's Law

- **The Significance of Relative Changes**
  - Greater changes occur at shallower depths
    - Pressure doubles during a descent from the surface to 10 m / 33 ft
    - Then, from 10 m / 33 ft, it does not double again until 30 m / 99 ft

Depth in Seawater		Ambient Pressure	Volume	Density
0 m	0 ft	1 bar / atm	x 1	x 1
10 m	33 ft	2 bar / atm	x 1/2	x 2
20 m	66 ft	3 bar / atm	x 1/3	x 3
30 m	99 ft	4 bar / atm	x 1/4	x 4
40 m	132 ft	5 bar / atm	x 1/5	x 5
50 m	165 ft	6 bar / atm	x 1/6	x 6

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Boyle's Law

- **The Significance of Relative Changes**
  - Greater changes occur at shallower depths
    - Volume increases by only 25% during an ascent from 40 m / 132 ft to 30 m / 99 ft
    - It increases by 100% from during an ascent from 10 m / 33 ft to the surface

Depth in Seawater		Ambient Pressure	Volume	Density
0 m	0 ft	1 bar / atm	x 1	x 1
10 m	33 ft	2 bar / atm	x 1/2	x 2
20 m	66 ft	3 bar / atm	x 1/3	x 3
30 m	99 ft	4 bar / atm	x 1/4	x 4
40 m	132 ft	5 bar / atm	x 1/5	x 5
50 m	165 ft	6 bar / atm	x 1/6	x 6

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Boyle's Law

- **The Significance of Relative Changes**
  - Greater changes occur at shallower depths
    - Important to equalize early during a descent
    - A diver may have more difficulty maintaining buoyancy control at shallower depths
    - Need vigilance to maintain a slow rate of ascent throughout the entire ascent, especially as the diver nears the surface

Boyle's Law

- **Pressure and Volume Calculations**
  - The general mathematical formula

Metric and Imperial

$$P_1 \times V_1 = P_2 \times V_2$$

Boyle's Law

- **Pressure and Volume Calculations**
  - To determine the new volume, after a given change in pressure

Metric and Imperial

$$V_2 = [\, P_1 \times V_1 \,] \,/\, P_2$$

Boyle's Law

- **Pressure and Volume Calculations**
  - To determine the new pressure, after a given change in volume

Metric and Imperial

$$P_2 = [P_1 \times V_1] / V_2$$

Boyle's Law

- **Pressure and Volume Calculations**
  - Knowing the time a certain supply of gas lasts at one depth, to determine the time at a new depth

Metric and Imperial

$$minutes_2 = [P_1 \times minutes_1] / P_2$$

Boyle's Law

- **Pressure and Volume Calculations**
  - Knowing the time a certain supply of gas lasts at one depth, to determine the new depth at which it will last a specific time

Metric and Imperial

$$P_2 = [P_1 \times minutes_1] / minutes_2$$

Charles' Law & Guy-Lussac's Law

- **Temperature and Volume**
  - Charles' Law: The volume of a gas increases or decreases by the same factor as its temperature
- **Temperature and Pressure**
  - Guy-Lussac's Law: The pressure of a gas increases or decreases by the same factor as its temperature

Both principles refer to absolute temperature (°Kelvin or °Rankin)

Charles' Law & Guy-Lussac's Law

- **How these Principles Relate to Diving**
  - Temperature affects both volume and pressure
    - Changes in volume occur only when the gas is confined in a flexible container
    - Changes in pressure occur in both flexible and rigid containers

Charles' Law & Guy-Lussac's Law

- **How these Principles Relate to Diving**
  - Similarly
    - A change in pressure or volume also will affect the temperature

Charles' Law & Guy-Lussac's Law

- **How these Principles Relate to Diving**
  - The most apparent effect involves the scuba cylinder
    - When a cylinder is heated, its pressure increases
    - When a cylinder is cooled, its pressure decreases
    - When a cylinder is filled, its temperature increases
    - When a cylinder is drained, its temperature decreases

Charles' Law & Guy-Lussac's Law

- **Temperature and Volume Calculations**
  - To determine the new volume of a gas (in a flexible container) after a change in temperature

Imperial

$$V_2 = V_1 \times [({}^{o}F_2 + 460) / ({}^{o}F_1 + 460)]$$

Each formula includes the conversion for absolute temperature

Charles' Law & Guy-Lussac's Law

- **Temperature and Pressure Calculations**
  - To determine the new pressure of a gas after a change in temperature

Imperial

$$psi_2 = \{ (psi_1 + 14.7) \times [({}^{o}F_2 + 460) / ({}^{o}F_1 + 460)] \} - 14.7$$

Each formula includes the conversion for absolute temperature

Charles' Law & Guy-Lussac's Law

- **Quick Estimate for Temperature and Pressure**
  - In the real world of diving

Imperial

1ºF = 5 psi

Dalton's Law

- **Partial Pressure**
  - The total pressure exerted by a mixture of gases is equal to the sum of the pressures of each of its component gases, with each component gas acting as if it alone was present and occupied the total volume
    - Each gas, within a mixture, has its own pressure (based upon its percentage in the mixture)
    - Each gas is unaffected by any other gas in the mixture

Dalton's Law

- **Partial Pressure**

Depth in Seawater		Ambient Pressure	Partial Pressures in Air	
			Oxygen (21%)	Nitrogen (79%)
0 m	0 ft	1 bar / atm	0.21 bar / atm	0.79 bar / atm
10 m	33 ft	2 bar / atm	0.42 bar / atm	1.58 bar / atm
20 m	66 ft	3 bar / atm	0.63 bar / atm	2.37 bar / atm
30 m	99 ft	4 bar / atm	0.84 bar / atm	3.16 bar / atm
40 m	132 ft	5 bar / atm	1.05 bar / atm	3.95 bar / atm
50 m	165 ft	6 bar / atm	1.26 bar / atm	4.74 bar / atm

Dalton's Law

- **Partial Pressure**
  - As depth varies
    - Percentage of each gas remains constant
    - Partial pressure of each gas varies with depth

Dalton's Law

- **How this Principle Relates to Diving**
  - Physiological impact of a gas depends upon its partial pressure
    - When breathing air at 40 m / 132 ft
      - The PO_2 is 1.05 atm, which is about the same as breathing 100% oxygen at the surface
      - The PN_2 is 3.95 atm, which is almost four times more than breathing 100% nitrogen at the surface

Dalton's Law

- **How this Principle Relates to Diving**
  - Ambient pressure, as well as the pressure of the breathing mixture inside a diver's lungs, remains constant at a given depth
    - Altering the percentages of the gases in the mixture allows more effective control of the physiological impact of each gas
    - This is the foundational concept for nitrox and other breathing mixtures

Dalton's Law

- **How this Principle Relates to Diving**
  - Partial pressures in air and nitrox

Depth in Seawater		Ambient Pressure	Partial Pressures in Air		Partial Pressures in Nitrox	
			Oxygen (21%)	Nitrogen (79%)	Oxygen (40%)	Nitrogen (60%)
0 m	0 ft	1 bar / atm	0.21 bar / atm	0.79 bar / atm	0.40 bar / atm	0.60 bar / atm
10 m	33 ft	2 bar / atm	0.42 bar / atm	1.58 bar / atm	0.80 bar / atm	1.20 bar / atm
20 m	66 ft	3 bar / atm	0.63 bar / atm	2.37 bar / atm	1.20 bar / atm	1.80 bar / atm
30 m	99 ft	4 bar / atm	0.84 bar / atm	3.16 bar / atm	1.60 bar / atm	2.40 bar / atm

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Dalton's Law

- **How this Principle Relates to Diving**
  - Equivalent air depth (nitrogen exposure)

Depth in Seawater		Ambient Pressure	Partial Pressures in Air		Partial Pressures in Nitrox	
			Oxygen (21%)	Nitrogen (79%)	Oxygen (40%)	Nitrogen (60%)
0 m	0 ft	1 bar / atm	0.21 bar / atm	0.79 bar / atm	0.40 bar / atm	0.60 bar / atm
10 m	33 ft	2 bar / atm	0.42 bar / atm	1.58 bar / atm	0.80 bar / atm	1.20 bar / atm
20 m	66 ft	3 bar / atm	0.63 bar / atm	2.37 bar / atm	1.20 bar / atm	1.80 bar / atm
30 m	99 ft	4 bar / atm	0.84 bar / atm	3.16 bar / atm	1.60 bar / atm	2.40 bar / atm

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Dalton's Law

- **Partial Pressure Calculations**
  - To determine the partial pressure of oxygen and nitrogen in air or a nitrox mixture

Metric and Imperial

$PO_2 = P \times FO_2$ *and* $PN_2 = P \times FN_2$

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Dalton's Law

- **Partial Pressure Calculations**
  - To determine which mixture provides a specific partial pressure at a given ambient pressure

Metric and Imperial

FG = PG / P

Henry's Law

- **Partial Pressure and Gas Solubility**
  - At a constant temperature, the quantity of gas which is dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with the liquid

Henry's Law

- **Partial Pressure and Gas Solubility**
  - Additional issues
    - Equilibrium is not instantaneous, and it takes some time for the gaseous partial pressure and the dissolved gas tension to equalize
    - The rate at which a gas moves into solution depends upon the pressure gradient
    - Once dissolved, the gas spreads uniformly throughout the liquid
    - At equilibrium, the liquid is saturated with the gas at its then existing partial pressure

Henry's Law

- **Partial Pressure and Gas Solubility**

Partial Pressure of Gas	Maximum Quantity of Dissolved Gas
0.25 bar / atm	x .025
0.50 bar / atm	x 0.50
0.75 bar / atm	x 0.75
1 bar / atm	x 1
2 bar / atm	x 2
3 bar / atm	x 3
4 bar / atm	x 4
5 bar / atm	x 5

Henry's Law

- **Partial Pressure and Gas Solubility**
  - When the gaseous partial pressure is decreased, so that it is less than the dissolved gas tension . . .
    - The liquid is now super-saturated with that gas
    - The gas begins to move out of solution and returns to its gaseous state
    - The rate at which a gas moves out of solution depends upon the pressure gradient
    - If tension tolerance limits are exceeded, the gas quickly comes out of solution and forms bubbles within the liquid

Henry's Law

- **How this Principle Relates to Diving**
  - Helps to explain
    - Why a diver on-gasses nitrogen at depth
    - Why a diver off-gasses nitrogen during and after ascent
    - Why DCS can occur if a diver remains too long at depth, or ascends too quickly

Henry's Law

- **How this Principle Relates to Diving**
  - Also helps to explain
    - How other gases move into and out of the body
      - Oxygen
      - Carbon dioxide

Henry's Law

- **Gas Solubility Calculations**
  - Impractical for general diving applications
    - Because of the variability of solubility coefficients and the widely divergent tissues of the human body

Combined & Ideal Gas Laws

- **Pressure, Volume and Temperature**
  - Combined Gas Law: includes three variables in a single formula

Metric and Imperial

$$(P_1 \times V_1) / T_1 = (P_2 \times V_2) / T_2$$

T: absolute temperature (°Kelvin or °Rankin)

Combined & Ideal Gas Laws

- **Pressure, Volume, Temperature and Mass**
  - Ideal Gas Law: expanded concept beyond Combined Gas Law, also includes mass
    - Applies to a hypothetical "ideal" gas, but an actual gas might vary from this model

Metric and Imperial

$$P \times V = (n \times R) \times T$$

T: absolute temperature (ºKelvin or ºRankin)
n: number of moles (atomic and sub-atomic particles)
R: universal gas constant

Haldane's Decompression Model

- **Theoretical Tissue Compartments**
  - Recognizing the complexities of the human body, Haldane constructed a mathematical model with multiple theoretical tissue compartments
    - These compartments do not directly correspond to any actual tissues
    - Each compartment is defined by certain properties
    - Taken together these compartments mimic the overall process of nitrogen on-gassing and off-gassing within a diver's body

Haldane's Decompression Model

- **Half-Times**
  - Haldane assigned a half-time to each compartment
    - This is the time it takes for that compartment to go halfway, from its initial level of dissolved nitrogen at a certain depth, to its ultimate level of dissolved nitrogen at a new depth
    - Half-times accommodate the fact that on-gassing and off-gassing initially occur at faster rates, then slow as the pressure gradient narrows

Haldane's Decompression Model

- **Half-Times**

60 Minute Compartment Exposed to Increased Pressure	
Elapsed Time	On-Gassing Completed
Start	**0.0%**
1 hour	**50.0%**
2 hours	**75.0%**
3 hours	**87.5%**
4 hours	**93.8%**
5 hours	**96.9%**
6 hours	**98.5%**

5 Minute Compartment Exposed to Decreased Pressure	
Elapsed Time	Off-Gassing Completed
Start	**0.0%**
5 minutes	**50.0%**
10 minutes	**75.0%**
15 minutes	**87.5%**
20 minutes	**93.8%**
25 minutes	**96.9%**
30 minutes	**98.5%**

Haldane's Decompression Model

- **M-Values**
  - Haldane conducted experiments to determine the maximum quantity of excess nitrogen that could be held in solution by each tissue compartment during ascent, after time at depth
    - It is expressed as a factor (or percent) above the normal amount of nitrogen present in a saturated tissue at the surface

Haldane's Decompression Model

- **Haldane's Algorithm**
  - Complex mathematical computation
    - Haldane calculated the relevant information for each theoretical tissue compartment
    - Haldane found that different compartments would govern the time limits at different depths
    - Haldane projected a schedule of depth and time limits
      - First dive tables
      - Used by Royal Navy from 1907 to 1956

Haldane's Decompression Model

- **Haldane's Algorithm**
  - Though highly theoretical in nature, time has proven Haldane's methodology to be valid

Haldane's Decompression Model

- **Modern Dive Tables and Dive Computers**
  - Over the years researchers have continued to refine and build upon Haldane's work
    - Expanded the number of tissue compartments
    - Recalculated the applicable M-values
    - Altered the specified ascent rates
    - Assigned dissimilar rates for on-gassing and off-gassing
    - Made other modifications to the algorithm

Haldane's Decompression Model

- **Modern Dive Tables and Dive Computers**
  - Today most dive tables and dive computers rely on an algorithm derived, directly or indirectly, from Haldane's decompression model


Summary
Introduction
Properties of Water
Archimedes' Principle
Principles of Pressure
Boyle's Law
Charles' Law & Guy-Lussac's Law
Combined & Ideal Gas Laws
Dalton's Law
Henry's Law
Haldane's Decompression Model
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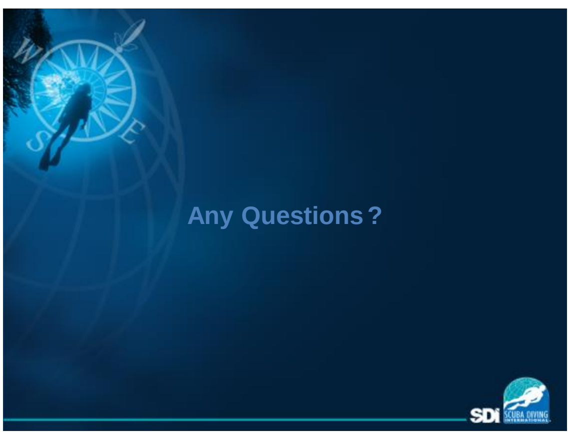
Any Questions ?
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