Gas Laws

Presented by the NOAA Diving Center
Seattle, Washington

Global View

- Boyle’s Law
- Dalton’ s Law
- Charles Law
- Gay-Lussac’s law
- Henry’s Law
- Gas Laws Relevance to Diving
- Gas Laws Formulas and Calculations
- Key Points

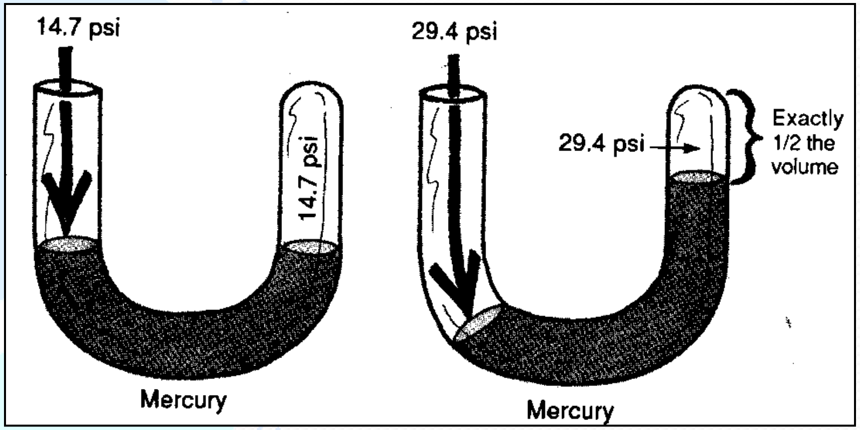
Boyle’s Law

- Definition: At constant temperature, the volume of a gas varies inversely with absolute pressure, while density varies directly with absolute pressure
- Relevance: Mechanical effects of pressure (e.g., buoyancy issues, barotrauma injuries, air-filled spaces in the human body)

As pressure increases, volume decreases, and vice-versa

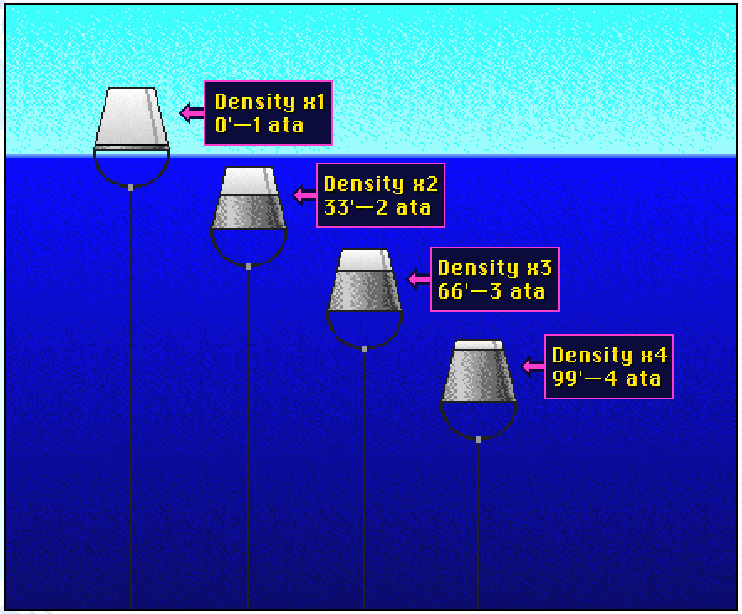
Pressure/Volume Relationship

- Robert Boyle (1660) did early experiments with pressure and volume relationships
- Determined that doubling the pressure on a gas reduced volume of gas by one-half



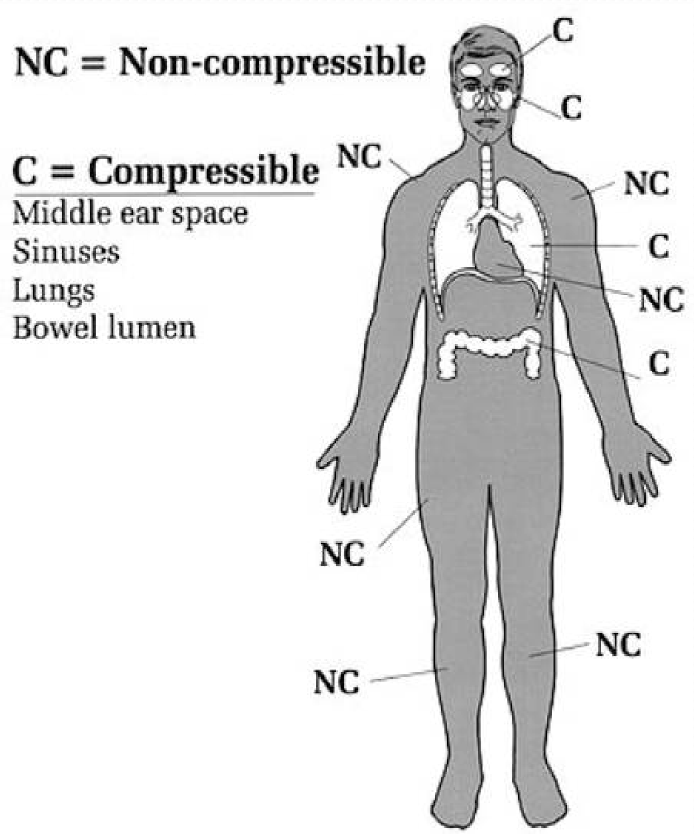
Direct Effects of Pressure

Depth	Pressure	Volume
0’	1 ATM	1
33’	2 ATA	1/2
66’	3 ATA	1/3
99’	4 ATA	1/4



Direct Effects of Pressure

- Bone, muscle, blood and solid organs: non-compressible
    - Not affected by the pressure changes at depth
- Lungs, middle ears, sinuses nasal passages, hollow organs, tooth cavities: compressible
    - Affected by the pressure changes at depth



Boyle's Law Formula

- $P_1V_1 = P_2V_2$

P_1 = Starting Pressure (ATA)
V_1 = Starting Volume
P_2 = Ending Pressure (ATA)
V_2 = Ending Volume

Note: Always use absolute pressure when working Boyle's gas law problems

Formula Rules

For correct calculations:

1. Determine known and unknown variables
2. Set up your formula
3. Express variables in units (always use absolute pressures and temperatures)
4. Substitute variables into formula and solve
5. Cancel like units
6. Express answer in units specified: psig, psia, fsw, ATA

Using Boyle’s Law

- Example #1:
  - A diver releases a balloon containing 0.25 cf of air at a depth of 3 ATA. Assuming no temperature change, what volume of gas will the balloon contain when it reaches the surface?

What is the unknown?

Using Boyle’s Law

Calculating question #1:

- Determine variables:
  - P_1 = Start Pressure = 3 ATA
  - P_2 = End Pressure = 1 ATA
  - V_1 = Start Volume = 0.25 cf
  - V_2 = End Volume = ? cf
- Set up formula to solve for V2

Use the Formula Rules as a check list

Using Boyle's Law

Answer to question #1:

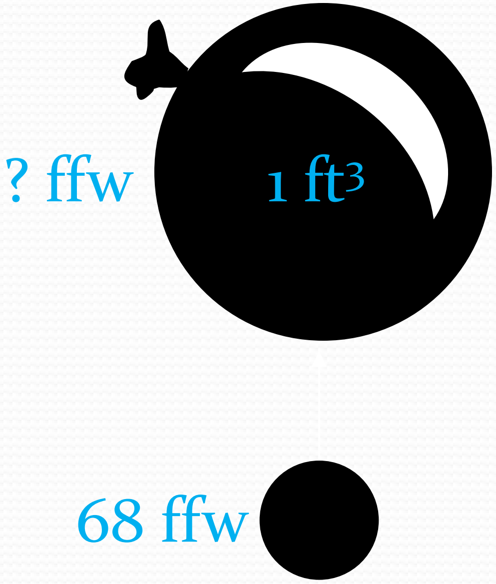
$$V_2 = \frac{P_1 V_1}{P_2} = \frac{3\ \cancel{\text{ATA}} \times 0.25\ \text{cf}}{1\ \cancel{\text{ATA}}} = \frac{0.75\ \text{cf}}{1} = \mathbf{0.75\ cf}$$

Note: Reducing pressure to 1/3 of initial force tripled the volume

Using Boyle's Law

Example #2:

If a balloon contains 0.4 cf of air at a depth of 68 ffw, at what depth will the volume of the balloon be 1.0 cf?



What is the unknown?

Using Boyle’s Law

Calculating example #2:

- Determine variables:
  - P_1 = Start Pressure = $\dfrac{(68 \text{ ffw} + 34 \text{ ffw})}{34 \text{ ffw}} = 3 \text{ ATA}$
  - V_1 = Start Volume = 0.4 cf
  - V_2 = End Volume = 1.0 cf
  - P_2 = End Pressure = ? ffw
- Set up formula to solve for P_2

Apply the Formula Rules

Using Boyle's Law

Answer to question #2:

$$P_2 = \frac{P_1 V_1}{V_2} = \frac{3 \text{ ATA x } 0.4 \cancel{\text{cf}}}{1 \cancel{\text{cf}}} = \frac{1.2 \text{ ATA}}{1} = 1.2 \text{ ATA}$$

Convert ATA to depth…

1.2 ATA - 1.0 ATM = 0.2 ATM x 34 ffw = **6.8 ffw**

Using Boyle's Law

OR

$$P_2 = \frac{P_1 V_1}{V_2} = \frac{44.1 \text{ psia x } 0.4 \cancel{\text{cf}}}{1 \cancel{\text{cf}}} = \frac{17.64 \text{ psia}}{1}$$

$$17.64 \text{ psia} - 14.7 \text{ psi} = \frac{2.94 \cancel{\text{psig}}}{0.432 \cancel{\text{psig}}/\text{ffw}} = \mathbf{6.8 \text{ ffw}}$$

Dalton’s Law

- Definition: The total pressure exerted by a mixture of gases is equal to the sum of the pressures that would be exerted by each of the gases if it alone were present and occupied the total volume
- Relevance: Decompression, gas toxicity, use of breathing mixtures other than air, maximum operating depths for diving, etc.

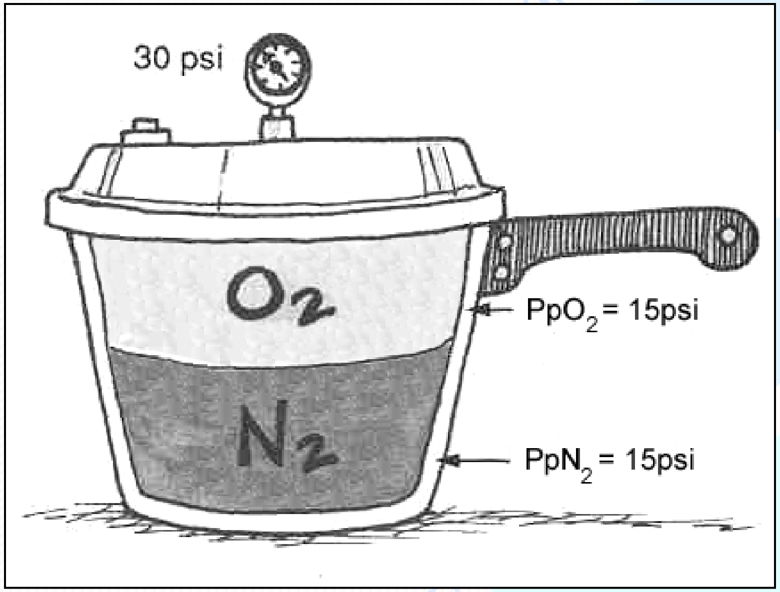
As pressure increases, partial pressure increases and vice versa

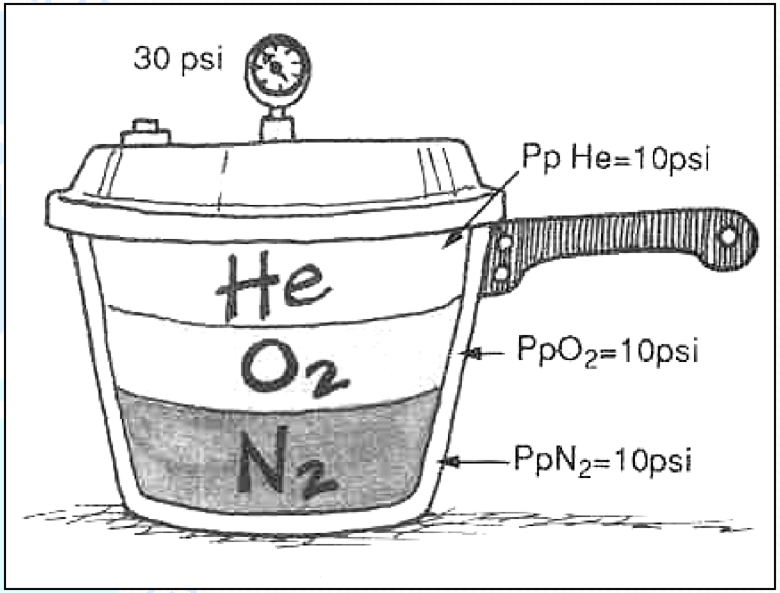
Dalton’s Law Formula

- In a gas mixture, the portion of the total pressure contributed by a single gas is called the “partial pressure” of that gas
- Formula: $P_{Total} = P_{P_1} + P_{P_2} + P_{Pn}$

P_{Total} = total pressure of the gas
P_{P_1} = partial pressure of gas component 1
P_{P_2} = partial pressure of gas component 2
P_{Pn} = partial pressure of other gas components

Dalton’s Law Formula

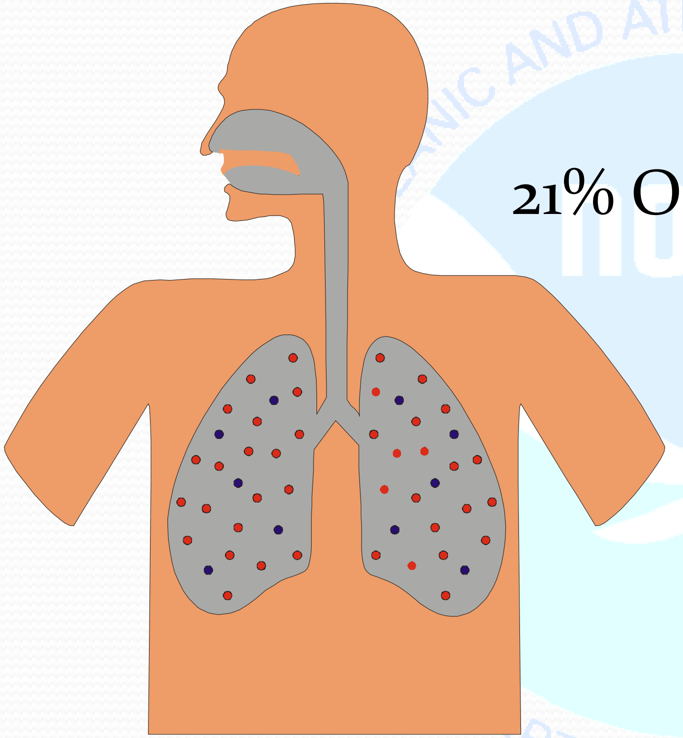




Partial Pressure VS. Depth - 1

21% O_2 – 79% N_2

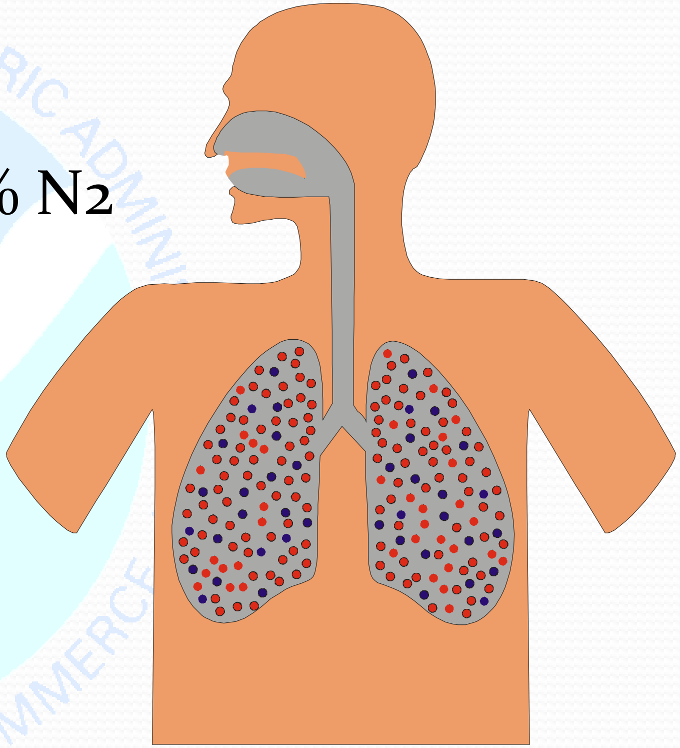
Surface (1 ATA)



Oxygen Partial Pressure = 0.21 ATA

Nitrogen Partial Pressure = 0.79 ATA

99 feet (4 ATA)



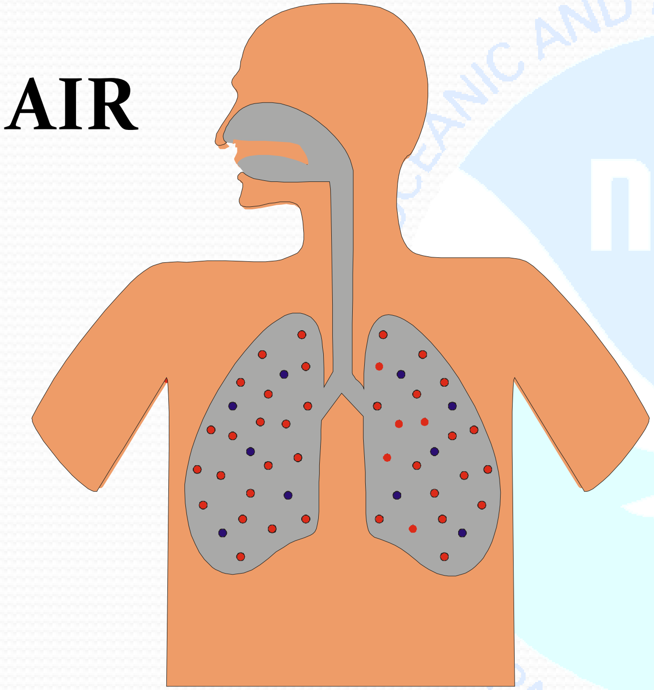
Oxygen Partial Pressure = 0.84 ATA

Nitrogen Partial Pressure = 3.16 ATA

Partial Pressure VS. Depth - 2

Surface (1 ATA)

AIR



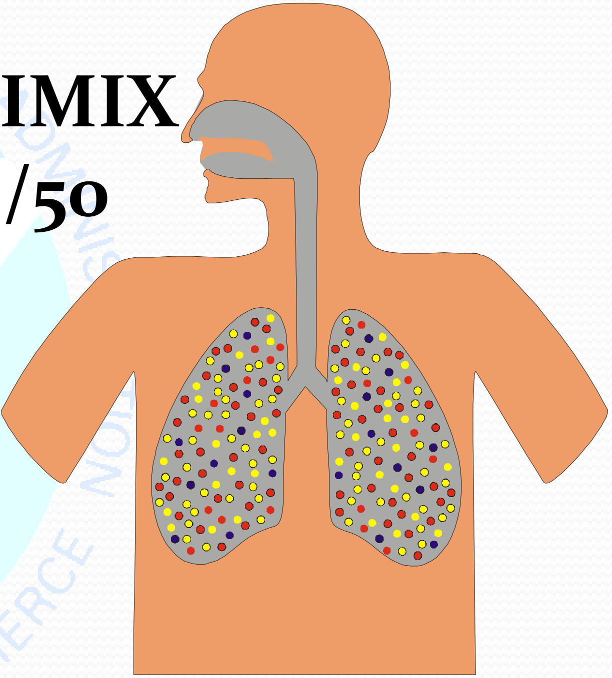
Partial Pressures

Nitrogen	Oxygen	Helium
.79	.21	0.0

300 feet (10 ATA)

TRIMIX

10/50



Partial Pressures

Nitrogen	Oxygen	Helium
4.0	1.0	5.0

Partial Pressure vs Percent

- Gas partial pressures relate to the force exerted by each molecule in a mixture and typically increase during descent and decrease during ascent of a dive
- Gas percentages define the ratios between the *number of gas molecules* in a mixture and typically remain constant throughout a dive

Percentage is only a means of calculating partial pressure

Partial Pressure

FSW	ATMOSPHERES ABSOLUTE			PSI ABSOLUTE			mmHg ABSOLUTE		
		N2	O2		N2	O2		N2	O2
0'	1 ATA	0.79	0.21	14.7 PSIA	11.6	3.1	760	600.4	159.6
33'	2 ATA	1.58	0.42	29.4 PSIA	23.2	6.2	1520	1200.8	319.2
66'	3 ATA	2.37	0.63	44.1 PSIA	34.8	9.3	2280	1801.2	478.8
99'	4 ATA	3.16	0.84	58.8 PSIA	46.4	12.4	3040	2401.6	638.4
132'	5 ATA	3.95	1.05	73.5 PSIA	58	15.5	3800	3002	798

Partial Pressure

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		N2	O2		N2	O2		N2	O2
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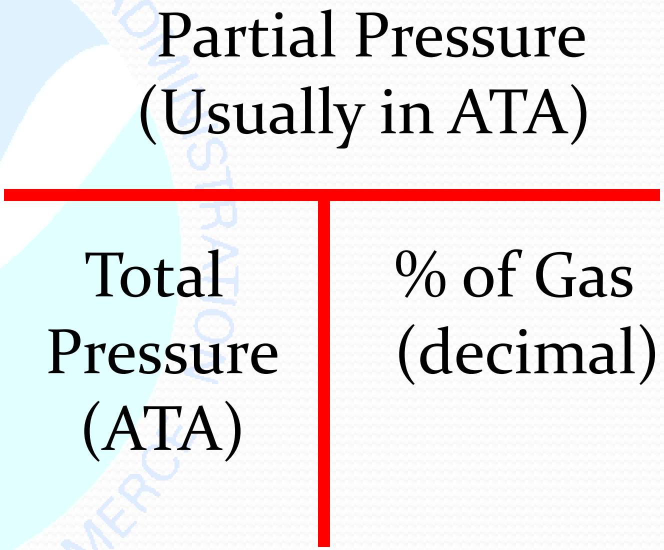
132'	5 ATA	3.95	1.05	73.5 PSIA	58	15.5	3800	3002	798

Dalton’s Law Calculations

- Partial pressure variables:
  - The total (absolute) pressure
  - The percent of gas in question
- The “T” formula
  - Any easy way to manipulate the critical variables for calculating partial pressure


Partial Pressure
(Usually in ATA)

Total Pressure (ATA)

% of Gas (decimal)

Using Dalton’s Law

Question #1:

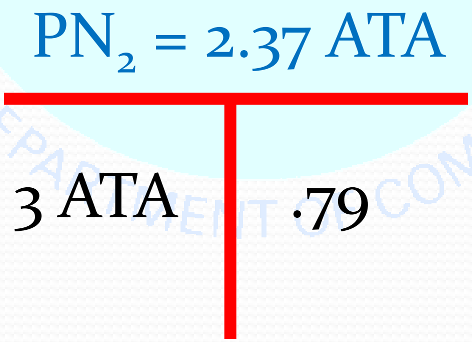
- What is the partial pressure of nitrogen (ATA) in air inside a balloon at a depth of 66 fsw**?**

Which variable in the “T” should be used**?**

Using Dalton’s Law

Calculating question #1:

- Determine variables:
  - P_T = (66 fsw + 33 fsw) divided by 33 fsw = 3 ATA
  - % nitrogen = 0.79 in air
  - PN_2 = **?**
- Substitute variables into “T” formula and solve for P_P



Using Dalton’s Law

Question #2:

- What is the partial pressure of oxygen in a scuba cylinder filled to 3,000 psig with NOAA Nitrox 32?

Using Dalton’s Law

Calculating question #2:

- Determine variables:
  - P_T = 3,000 psig + 14.7 psi = 3,014.7 psia
  - 3,014.7 divided by 14.7 = 205.08 ATA
  - % oxygen = 0.32 in Nitrox 32
  - PO_2 = **?**
- Substitute variables into “T” formula and solve for PO_2 then PN_2

PO2 65.63 ATA

205.08 ATA | .32

Remember, the sum of the partial pressures has to equal the total pressure!

Using Dalton’s Law

Question #3:

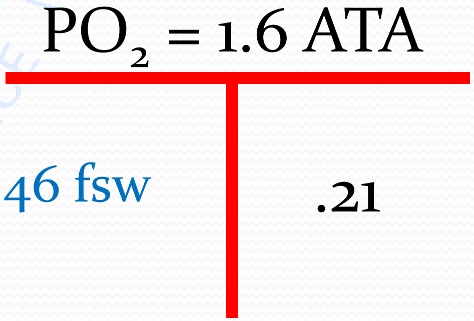
- At what depth in the sea will the partial pressure of oxygen in air equal 1.6 ATA?
- Note: Solve Total Pressure variable in FSW

Note: Oxygen becomes toxic from a central nervous system perspective when the PO_2 exceeds 1.6 ATA.

Using Dalton’s Law

Calculating question #3:

- Determine variables:
  - P_T = **?**
  - % oxygen = 0.21 in air
  - PO_2 = 1.6 ATA
- Substitute variables into “T” formula, solve for P_T, then convert P_T to depth (fsw)



[7.62 ATA x 33 FSW/ATM] – 33 FSW/ATM = 218.46 fsw

Charles' Law

- Definition: At a constant pressure, the volume of a gas varies directly with absolute temperature
- Relevance: Effects of temperature on flexible air-filled spaces (e.g., buoyancy issues, lift bags)

Effects of Temperature

- As temperature increases, volume increases
- As temperature decreases, volume decreases

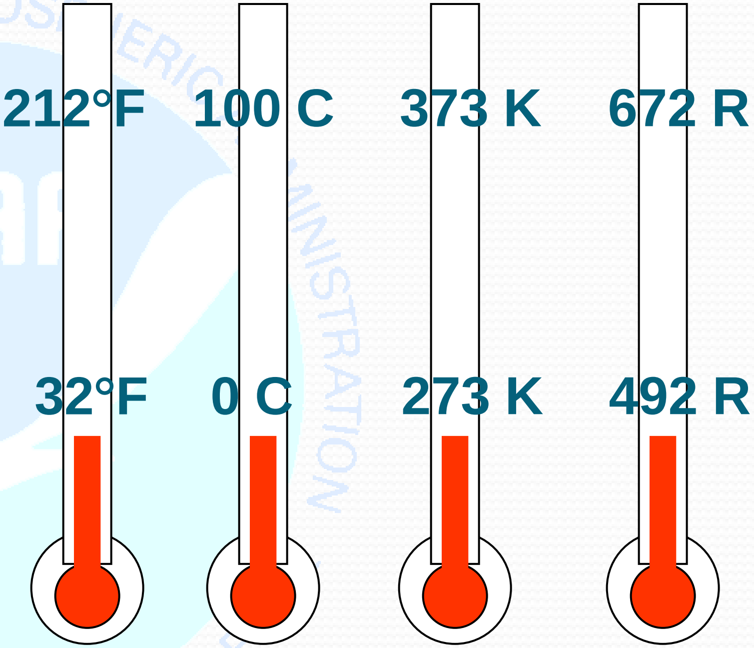
Charles' Law Formula

- $\frac{V_1}{V_2} = \frac{T_1}{T_2}$
  - V_1 = Starting volume
  - T_1 = Starting temperature (ATA)
  - V_2 = Ending Volume
  - T_2 = Ending temperature (ATA)

Note: Always use absolute temperature when working Charles' gas law problems

Absolute Temperature

- Temperature scales:
  - Fahrenheit (F)
  - Celsius (C)
  - Rankine (R)
  - Kelvin (K)
- Absolute temperature conversions:
  - °F = (9/5 x C) + 32
  - C = 5/9 (°F - 32)
  - Rankine = °F + 460
  - Kelvin = C + 273



Two sets of equal temperatures

Temperature Conversion - 1

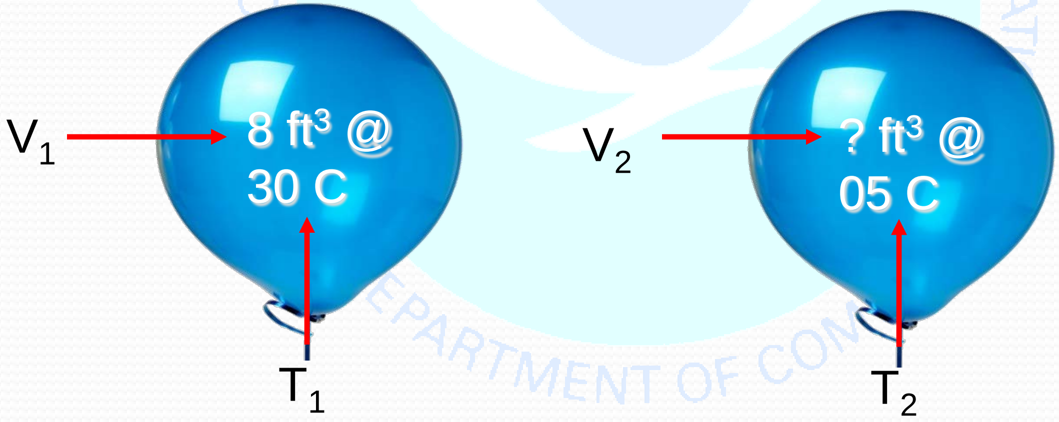
- Question #1: 70 degrees F = _____ C?
  - Formula: $C = 5/9\ (°F - 32)$
- Answer
  - $C = 5/9\ (70 - 32)$
  - $C = 0.556 \times 38$
  - $C = 21.13$

Temperature Conversion - 2

- Question #2: 17 C = ______ K?
  - Formula: Kelvin = C + 273
- Answer
  - Kelvin = 17 C + 273
  - Kelvin = 290

Using Charles’ Law

- Example #1:
  - A balloon contains 8.0 cf of air at a temperature of 30 C. What will the volume of air be in the balloon when the temperature of the air inside is 5 C?



Using Charles' Law

- Calculating example #1:
  - Determine variables:
    - V_1 = Start Vol. = 8.0 cf
    - T_1 = Start Temp. = 30 C + 273 = 303 K
    - V_2 = End Volume = ?cf
    - T_2 = End Temp. = 5 C + 273 = 278 K
  - Set up formula, substitute, and solve for V_2

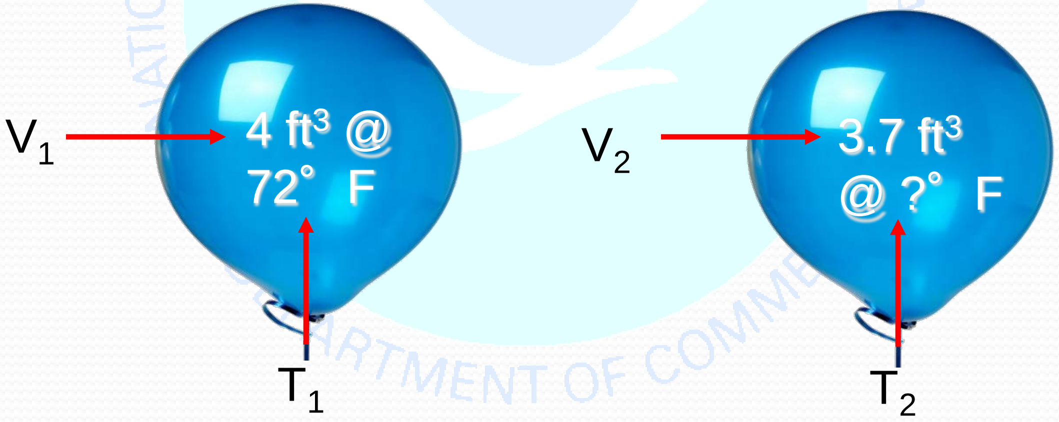
Using Charles’ Law

- Answer to example #1:

$$V_2 = \frac{V_1T_2}{T_1} = \frac{8.0\text{ cf X }278\,\cancel{K}}{303\,\cancel{K}} = \frac{2{,}224\text{ cf}}{303} = 7.34\text{ cf}$$

Using Charles’ Law

- Example #2:
  - A balloon contains 4.0 cf of air at a temperature of 72°F. What will the temperature be when the volume of the balloon is 3.7 cf ?



Using Charles' Law

- Calculating example #2:
  - Determine variables:
    - V_1 = Start Vol. = 4.0 cf
    - T_1 = Start Temp. = 72°F + 460 = 532 R
    - V_2 = End Volume = 3.7cf
    - T_2 = End Temp. = ?°F
  - Set up formula, substitute, and solve for T_2

Using Charles' Law

- Answer to example #2:

$$T_2 = \frac{V_2T_1}{V_1} = \frac{532\text{ R x }3.7\ \cancel{\text{cf}}}{4.0\ \cancel{\text{cf}}} = \frac{1968\text{ R}}{4.0} = 492\text{ R} =$$

$$492\text{ R} - 460 = 32.1^{\circ}\text{ F}$$

Gay-Lussac’s Law

- Definition: At constant volume, the pressure of a gas varies directly with absolute temperature
- Relevance: Pressure/temperature changes in rigid air-filled spaces (e.g. scuba cylinders, hyperbaric chambers, seafloor habitats)

Effects of Temperature: Lussac

- As temperature increases, pressure increases
- As temperature decreases, pressure decreases

Rule of Thumb: Steel scuba tank pressure increases about 5 psi per ° F. of temperature change; aluminum about 6 psi.

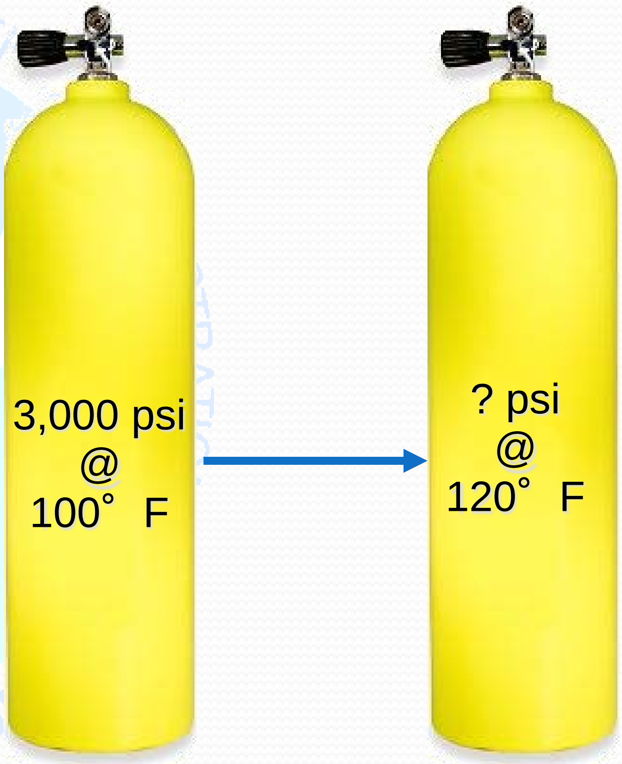
Gay-Lussac’s Law Formula

- $\frac{P_1}{P_2} = \frac{T_1}{T_2}$
  - P_1 = Starting pressure (ATA)
  - T_1 = Starting temperature (ATA)
  - P_2 = Ending pressure (ATA)
  - T_2 = Ending pressure (ATA)

Always use absolute pressure and temperature when working Gay-Lussac’s gas law problems

Using Gay-Lussac’ s Law

- Example #1:
  - An 80 cf aluminum scuba cylinder is filled to 3000 psig and the temperature inside the tank reaches 100°F.
  - How many PSI will be in the tank if the temperature of the gas increases to 120°F?



Using Gay-Lussac’ s Law

- Calculating example #1:
  - Determine variables:
    - P1 = Start pressure = 3,000 psig + 14.7 psi = 3,014.7 psia
    - T1 = 100°F. + 460 = 560 R.
    - P2 = End Pressure = ?psig
    - T2 = End Temp. = 120°F. + 460 = 580 R.
  - Set up formula, substitute, and solve for P2.

Using Gay-Lussac’s Law

- Answer to example #1:

$$P_2 = \frac{P_1T_2}{T_1} = \frac{3{,}014.7\ \text{psia x } 580\cancel{^{\circ}\text{R}}}{560\cancel{^{\circ}\text{R}}} = \frac{1{,}748{,}526\ \text{psia}}{560} =$$

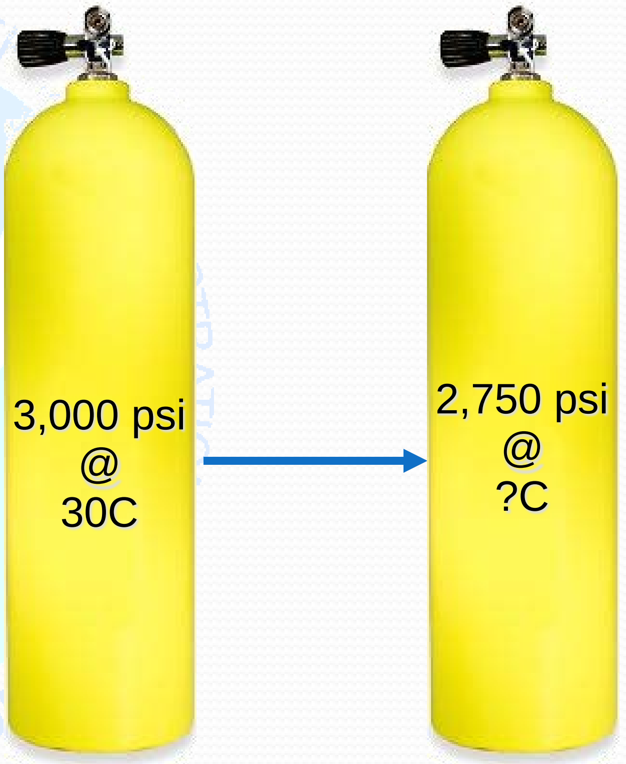
3,122.34 psia - 14.7 psi = 3,107.64 psig

Note: Estimated pressure increase before calculating is: 6 psi x 20° F. = +120 psig increase.

Calculated pressure increase is +107 psig!

Using Gay-Lussac’s Law

- Example #2:
  - An 80cf aluminum scuba cylinder at a temperature of 30 C with 3000 psig will decrease to 2750 psig at what temperature C ?



3,000 psi
@
30C

2,750 psi
@
?C

Using Gay-Lussac’ s Law

- Calculating example #2:
  - Determine variables:
    - P1 = Start pressure = 3,000 psig + 14.7 psi = 3,014.7 psia
    - T1 = 30 C + 273 = 303 K
    - P2 = End pressure = 2750 psig + 14.7 psi + 2764.7 psia
    - T2 = End Temp. = ?C
  - Set up formula, substitute, and solve for T2.

Using Gay-Lussac's Law

- Answer to example #2:

$$T_2 = \frac{T_1P_2}{P_1} = \frac{303\ \text{K} \times 2764.7\ \cancel{\text{psia}}}{3014.7\ \cancel{\text{psia}}} = 278\ \text{K} =$$

$$\begin{array}{r} 278\ \text{K} \\ -273 \\ \hline 5\ \text{C} \end{array}$$

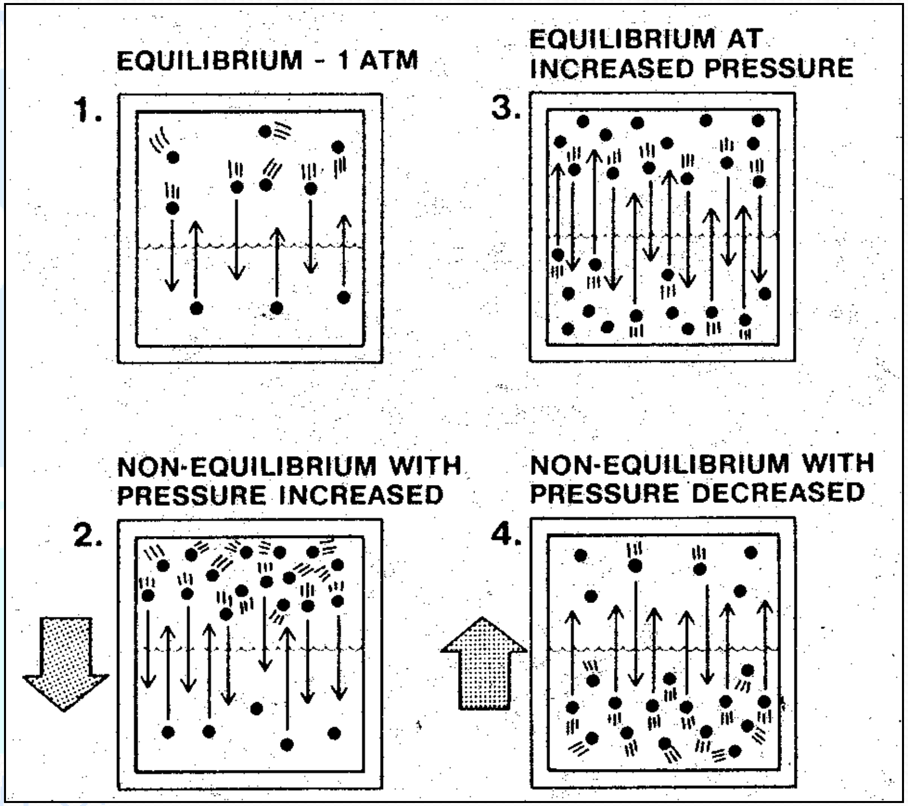
Henry’s Gas Law

- Definition: “The amount of any gas that will dissolve in a liquid at a given temperature is a function of the partial pressure of the gas that is in contact with the liquid and the solubility coefficient of the gas in the particular liquid”
- Relevance: Decompression sickness (DCS), decompression tables and dive computer development

At surface our bodies are saturated with $\approx$ 1 liter of N_2. If a diver stays at 60 feet for an extended period of time, their body would be saturated with $\approx$ 3 liters of N_2

Gas Absorption & Elimination

- During descent excess gas dissolves into a diver's body
- At the bottom, gas continues to dissolve until the diver's body is "saturated" for a given pressure
- During ascent, gas comes out of solution



The Soda Pop Analogy

- Soda is saturated with gas (CO_2)
- Pressure (sealed bottle) keeps the gas in solution
- Rapidly reducing the pressure causes gas to rush out of solution and form bubbles
- A saturated diver ascending rapidly can experience a similar effect!
- Note: A bottle of soda with a slow leak does not fizz when opened slowly

Always ascend slowly to allow excess gas to escape!

Knowledge check…..

- Boyle's gas law deals with:
  - Pressure and temperature
  - Pressure and volume
  - Volume and temperature
- According to Boyle's gas law, a balloon filled with air at depth inside a hyperbaric chamber will _____ during ascent?
  - Increase in size
  - Decrease in size
  - Remain the same

Knowledge check…..

- Dalton's gas law deals with:
  - Partial pressures
  - Gas absorption and elimination
  - Pressure/temperature relationships
- According to Dalton's gas law, the partial pressure of a gas ____ on descent and ____ on ascent.
  - Increases; decreases
  - Decreases; increases

Knowledge check…..

- Charles' gas law deals with:
  - Pressure and temperature
  - Pressure and volume
  - Volume and temperature
- According to Charles' gas law, a filled balloon will ____ in size with a/an ____ in temperature?
  - Increase; decrease
  - Decrease; increase
  - Increase; increase
  - Decrease; decrease

Knowledge check…..

- Gay-Lussac’s gas law deals with:
  - Pressure and temperature
  - Pressure and volume
  - Volume and temperature
- According to Gay-Lussac’s gas law, a hyperbaric chamber will _____ in temperature during pressurization to depth?
  - Increase
  - Decrease
  - Remain the same

Knowledge check…..

- Henry’s gas law deals with:
  - Gas absorption and elimination
  - Tissue half-times
  - Decompression
- According to Henry’s gas law, the amount of gas that will be absorbed into the body is based upon:
  - The differential partial pressure of the gas inside and outside the liquid
  - Solubility coefficient of the gas in the liquid
  - The gender of the individual

Questions?