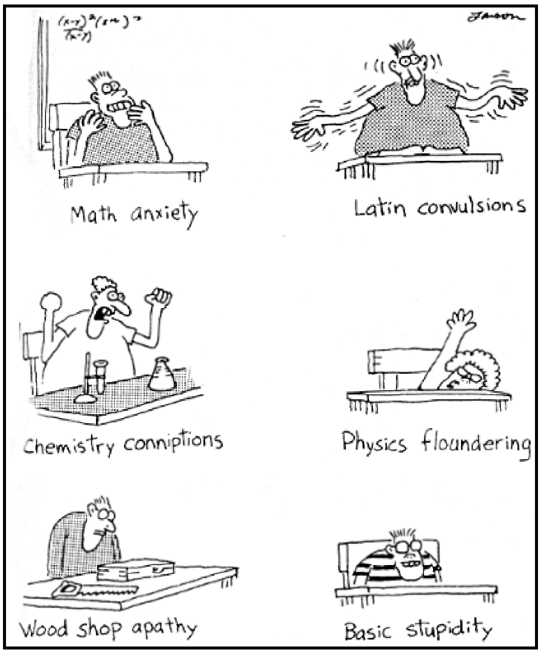
Section 3 — Calculations, Diving Physics and Physiology



Classroom afflictions.[1]

1 Copyright © The Far Side, Last Impressions, 2002, Larson. (Stolen and used without permission!)

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1 CHAPTER 1 – INTRODUCTION

GENERAL

ADAS COMPETENCY

Diving physics, physiology and associated calculations.

Ensure safety of others in a hyperbaric environment, in changing pressures and in an underwater environment.

Ensure safety of others in working underwater, in relation to buoyancy, light, sound and thermal conductivity underwater and their implications for the diver.

Perform calculations relating to breathing gases, buoyancy and lifting.

Physics relates to the science of matter and energy and their interactions.

Physiology relates to the functions and vital processes within the body. Anatomy is the organisation and structure of the body – the housing in which the processes of physiology are carried on.

Human physiology is well suited to environmental conditions on land. However, the physics of gases and liquids results in a vastly different set of conditions underwater. The effect of pressure, pressure differentials and the behaviour of gases has a tremendous impact on the physiological processes within the human body when exposed to the underwater environment.

The body is also not very successful in handling interruptions of the respiratory and circulatory systems. A person can function for only a few minutes without breathing before the cells begin to die. If the heart stops beating, the cells in the brain will begin to suffer damage almost immediately. The respiratory and circulatory systems are so vital to the body that anything that interferes with them can result in serious problems. By its very nature, the underwater environment poses continuing hazards to respiration and circulation.

A dive supervisor must have a particularly thorough understanding of both physics and physiology to understand the basis of possible problems, the best ways to prevent problems and the best treatment options if an accident occurs.

The nature of the underwater environment means that problems can escalate to emergencies very rapidly. This means that there is very little time for making decisions about what to do. The dive supervisor must simply know the fundamentals thoroughly and have a range of resources available to assist in risk management. These may be checklists, contingency plans and emergency response procedures that have all been prepared in advance. The key to diving safety is preparation, strict adherence to procedures and competence of the dive team and the dive supervisor.

Physics and physiology has been covered in detail in the technical diver training that you will have completed, and the information is available in the ADAS Part 1 manual or any reputable diving manual, including recreational diving manuals. A list of references is provided for you to refresh your memory of any of the issues.

Here we will look mainly at the implications for the dive supervisor for maintaining diver safety during and following a diving operation. You will need to have the knowledge and methods for ensuring:

- ✔ safety in a **hyperbaric** environment, in **changing pressures** and in an **underwater** environment,
- ✔ safety in working underwater, in relation to **buoyancy, light, sound and thermal conductivity** underwater, and

✔ how to perform calculations relating to breathing gases, buoyancy and lifting.

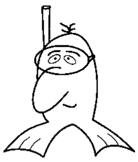
This chapter focuses mostly on a brief revision of the theory and on the calculations you may be required to perform. We will look in more detail at risk control measures in the chapter on managing risk.

SAFETY IN A HYPERBARIC ENVIRONMENT, IN CHANGING PRESSURES AND IN AN UNDERWATER ENVIRONMENT

The dive supervisor is responsible for the safety of the divers. He or she must therefore be familiar with all the health and safety issues associated with working in a hyperbaric environment and in an underwater environment. This refers to both the hyperbaric (high-pressure) environment underwater, in a habitat or in a chamber. The major safety concerns of a hyperbaric environment are related to the effects of rapidly changing pressures that are experienced in ascending or descending underwater or undergoing pressure changes in a habitat or chamber.

To select the best risk control measures to apply in a diving operation or actions to take in an emergency, the dive supervisor needs a thorough understanding of the physiology of the body and the mechanisms by which the hyperbaric environment and changing pressures adversely affect the body systems.

You need to:



✔ understand the behaviour of **gases** in changing pressures and temperatures,

✔ know which **body systems** are affected by high pressure and changing pressures,

✔ know the effects of **changing pressures** on body systems and the implications for the diver,

✔ apply mathematical concepts accurately in **calculations relating to gases** applicable to diving, and

✔ understand the reasons for the use of **mixed gas and rebreathing apparatus** in diving.

We will look at some specific risk controls for some of these areas in the chapter on managing risk.

2 CHAPTER 2 – PHYSICS OF DIVING

RELATIONSHIP BETWEEN PRESSURE, VOLUME AND TEMPERATURE OF GASES

ADAS COMPETENCY

Demonstrate an understanding of the relationship between pressure, volume and temperature of gases.

Define the following terms:

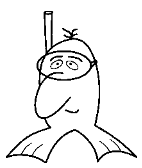
- ✔ **Atmospheric pressure**
- ✔ **Hydrostatic pressure**
- ✔ **Absolute pressure**
- ✔ **Ambient pressure**
- ✔ **Gauge pressure**

Describe the relationship between pressure and volume (Boyle's Law).

Calculate volume changes with changing depths and pressures.

Describe the relationship between pressure and temperature (Charles' Law).

Calculate pressure changes with changes in temperature.



■ GENERAL[2]

As land-based creatures, we know what to expect from our physical environment. This will all change as we go underwater. A sound understanding of basic physical properties will make our diving safer. The importance of such properties as pressure, buoyancy, temperature, light, sound and density will become evident during our dives. For instance, with or without scuba, a duck dive (forward head first dive) to a depth of two metres/seven feet may cause discomfort in the ears. This is a direct result of changing pressure. Taking a photograph underwater can present different challenges to those on land due to the changing effect of light. You will also learn how water affects vision and sound.

■ DEFINITIONS

This section defines the basic principles necessary to understand the underwater environment.

PRESSURE

Pressure is force acting on a unit of area. Expressed mathematically as;

$$\text{Pressure} = \frac{Force}{Area}$$

Pressure is usually expressed in kilograms per square centimetre (kg/cm^2) or pounds per square inch (psi).

ABSOLUTE TEMPERATURE

When temperature is measured on a number line, the freezing and boiling points of water appear as part of a continuing scale.

It should be obvious however, that the freezing point of water measured in degrees Celsius or degrees Fahrenheit is not the beginning of the number line for temperature.

Temperature can be reduced to an absolute zero point, which is practically impossible to reach.

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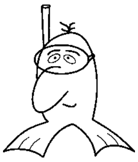
2 The text in this section is primarily drawn from the NASDS Australasia Inc. publication "Safe Scuba", ISBN 1 875 355 03 0, May 1995.

Both number lines are the same but use a different sized unit. The metric unit is degrees Celsius for which absolute zero is minus 273°. When converting degrees Celsius to absolute temperature they are called Kelvin after an eminent Scottish physicist called Lord Kelvin.

To convert degrees Celsius to absolute temperature (Kelvin) add 273°.

METRICS AND DIVING



When undertaking any calculation work involving diving, a thorough understanding of the metric system is essential. The metric system is based on units involving multiples of 10 and so all calculation work is considerably easier than when dealing with imperial units.

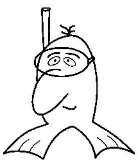
When discussing metrics, whether it be mass, volume, distance or pressure, common prefixes are used which represent the order of magnitude. For instance, kilo refers to 1000; therefore, 5 kilograms represent 5000 grams.

PREFIX	FRACTION OR MULTIPLE	SYMBOL
milli-	1/1000	m
centi-	1/100	c
deci-	1/10	d
deca-(or deka-)	X 10	D
hecto-(or hecta-)	X 100	h
kilo-	X 1,000	k
mega-	X 1,000,000	M

The basic metric units are:-

- ✔ Mass - grams (g)
- ✔ Volume - litres (l)
- ✔ Distance - metres (m)
- ✔ Pressure - pascals (Pa)

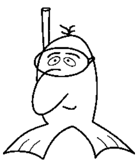
MASS



When dealing with the mass or, in simple terms the weight of an object, the term tonne represents 1,000 kilograms. That is, the tonne is another term for a megagram.

The basic unit for purposes of diving calculations is the kilogram, and it should be noted that 1 litre of fresh water weighs 1 kilogram. One millilitre of water weighs 1 thousandth of a kilogram or 1 gram.

VOLUME



When discussing fluids, the base unit of volume in the metric system is the litre. However, when discussing the volume of objects, we often talk in terms of cubic metres (m^3). The volume of a rectangular solid is determined by multiplying the object's length (L) by its breadth (B) by its height (H).

The relationship between litres and cubic metres must be understood to successfully complete some diving calculations.

1 cubic metre equals 1000 litres. Therefore, 1 cubic metre of fresh water weighs 1000 kilograms or 1 tonne.

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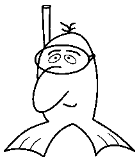
For small objects of irregular shape, the volume can be determined by immersing the object in a fluid and measuring the volume of the fluid displaced.

DENSITY

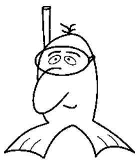


The density of a substance is an expression of its mass per unit volume. To calculate density, simply divide the object's mass by its volume.

✔ Density = Mass ÷ Volume. The unit for density is grams per cubic centimetre (g/cm^3).

In general terms, the greater the density of a substance the heavier the substance will be per unit volume. Lead has a greater density than aluminium. Therefore, if an equal volume of each metal were weighed the lead would far exceed the weight of the aluminium.

SPECIFIC GRAVITY

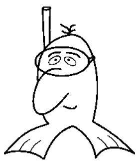


Specific gravity is a term used to compare the density of a substance relative to fresh water. Fresh water has a specific gravity or SG of 1. All other substances are rated from this benchmark.

If a substance has a specific gravity less than fresh water it will float while a substance with an SG greater than fresh water will sink.

Specific gravity also helps us to determine the weight of an object. If a metal has an SG of 4 then it is 4 times as dense as fresh water. A given volume of the metal will weigh 4 times more than the same volume of fresh water.

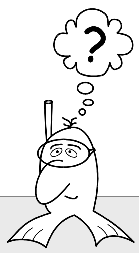
DISTANCE



The basic metric unit for distance is the metre. There are 1000 millimetres and 100 centimetres in a metre. 1000 metres make up 1 kilometre.

The weight of our atmosphere, approximately 320 kilometres/200 miles high, only produces a total pressure at sea level of one atmosphere.

■ PRESSURE



NTK!

Knowledge of the pressure depth relationship is fundamental to all aspects of diving theory.

Humans have evolved in an environment, which is relatively stable when considering pressure changes. The weight of our atmosphere, approximately 320 kilometres/200 miles high, only produces a total pressure at sea level of one atmosphere or approximately 100 kilopascals/14.7 psi. One needs to travel 5,000 metres/16,000 feet upwards to halve this pressure.

Since water is considerably denser than air, it creates a high-pressure environment. Consequently, we very quickly notice the increased pressure as we descend underwater. A depth of only ten metres/33 feet is required to produce another atmosphere of pressure. At ten metres/33 feet the “total” or “absolute pressure” is two atmospheres (200 kilopascals/ 29.4 psi), i.e. one atmosphere of air plus one atmosphere of water.

If we want to calculate the total or absolute pressure at any depth, the depth in metres/feet is divided by 10 metres or 33 feet and one atmosphere of air is added to it.

Pressure can therefore be equated with depth as a depth/pressure relationship.

$$\text{Absolute Pressure} = \frac{\text{Depth(m)}}{10} + 1 \quad \text{or;}$$

$$\text{Absolute Pressure} = \frac{\text{Depth (ft)}}{33} + 14.7$$

For every 10 metres/33 feet of seawater, an extra atmosphere (100 kilopascals/ 14.7 psi) is

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added to the total pressure. To convert atmospheres to kilopascals multiply by 100. To convert atmospheres to psi multiply by 14.7.

You may also see the term “bar or bars” used to describe pressure. The term “bar” refers to barometric pressure. Some cylinder pressure gauges are read in bars. Barometric pressure is only fractionally different from atmospheric pressure.

Problem: What is the absolute pressure at 37 metres in seawater?

Solution:

$$\text{Absolute Pressure} = \frac{37\text{m}}{10} + 1$$
$$\text{Absolute Pressure} = 3.7 + 1$$
$$\text{Absolute Pressure} = 4.7\text{ATA}$$

To double the absolute pressure one only has to descend to 10 metres/33 feet. To double the absolute pressure again, descend a further 20 metres/66 feet, i.e. descend from 10 metres/33 feet to 30 metres/99 feet. To double the absolute pressure yet again, it is necessary to descend a further 40 metres/131 feet, i.e. to descend from 30 metres/99 feet to 70 metres/230 feet. The important thing to note is that the greatest proportional pressure change occurs nearer the surface.

It is because of this, that the diver must take particular care when diving in the zero metre to ten metres depth range to avoid “Barotrauma” (pressure injury).

Another term that can be used for absolute pressure is “ambient pressure” — that is the total pressure surrounding the diver at any one time.

If depth gauges, pressure gauges and other pieces of equipment for measuring are to be used, they need to be calibrated to read zero at the surface, ten metres at ten metres and so on. That is, these instruments are calibrated to ignore the one atmosphere of air on the surface. They read in gauge units or “gauge pressure”.

All of the work with pressure and its effects on the body will have to take into account air pressure, so all future reference to pressure will be in absolute units unless otherwise stated.

PRESSURE CONVERSION

	EXACT	ACCEPTABLE APPROX	UNIT
1 Atmosphere =	0.1013	0.1	Mega-Pascals (MPa)
	101.3	100	Kilopascals (kPa)
	1.033	1	Kilograms/Centimetres squared (Kg/cm^2)
	1.013	1	Bars (Bar)
	1.013	1	Hectopascals
	760	760	Torr
	760.00	760	millimetres of mercury (mm Hg)
	29.921	30	inches of mercury (in Hg)
	14.696	15	Pounds/Inch squared (psi)
	33.044	33	feet of sea water
	33.932	34	feet of fresh water

With the wide acceptance of both metric and imperial units, pressure conversion becomes a necessary skill for occupational divers and supervisors.[3]

3 Table from the NASDS publication “Dive Supervisor’s handbook”, Third edition, 1993, ISBN 1 875 355 02 0.

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SUMMARY

To summarise, four terms are used to describe gas pressures:

Atmospheric Pressure

Results from the weight of atmospheric gases and acts on all bodies or structures in the atmosphere. Atmospheric pressure acts in all directions at any specific point. Since it is equal in all directions, its effects are usually neutralised. At sea level, atmospheric pressure is 1.033 kg/cm^2 (14.7 psi). At higher elevations, this value decreases. Pressures above 1.033 kg/cm^2 (14.7 psi) are often expressed in bar. For example, one bar is 1.033 kg/cm^2 (14.7 psi), 10 bar is 10.33 kg/cm^2 (147 psi) and 100 bar is 1033 kg/cm^2 (1470 psi).

Hydrostatic Pressure

Results from the weight of water (or any fluid) and acts upon any body or structure immersed in the water. Like atmospheric pressure, it is equal in all directions at a specific depth. Hydrostatic pressure is most important to a diver. It increases at a rate of 0.1033 kg/cm^2 per metre (0.445 psi per foot) of descent in seawater and 0.1 kg/cm^2 per metre (0.432 psi per foot) of fresh water.

Absolute Pressure

Is the sum of the atmospheric pressure (bar) and the hydrostatic pressure exerted on a submerged body. Absolute pressure is measured in bar absolute or kilograms per square centimetre absolute (kg/cm^2 absolute) (psi absolute).

Gauge Pressure

Is the difference between absolute pressure and a specific pressure being measured. Pressures are usually measured with gauges that are calibrated to read "0" at sea level when they are open to the air. Gauge pressure is therefore converted to absolute pressure by adding 1 bar if the dial reads in bar or 100 if the dial reads in kPa.

ADDITIONAL READING

Additional reading on this topic can be found in

✔ PADI Text "The Encyclopaedia of Recreational Diving" – Chapter One.

GAS THEORY RELEVANT TO THE DIVER

■ KINETIC THEORY AND GASES

Put in simple terms, matter is composed of atoms and molecules that can exist in three states: solids, liquids and gases.

Characteristics of solids, liquids and gases:

✔ Solids have their own shape, own volume and are non-compressible. The molecules are fixed but vibrating.

✔ Liquids have their own volume but take the shape of the container they are in. The molecules are described as less tightly packed and slipping. Liquids are also non-compressible.

✔ Gases have neither their own shape nor volume and expand indefinitely to occupy their container. The molecules are described as being in constant random motion and are compressible.

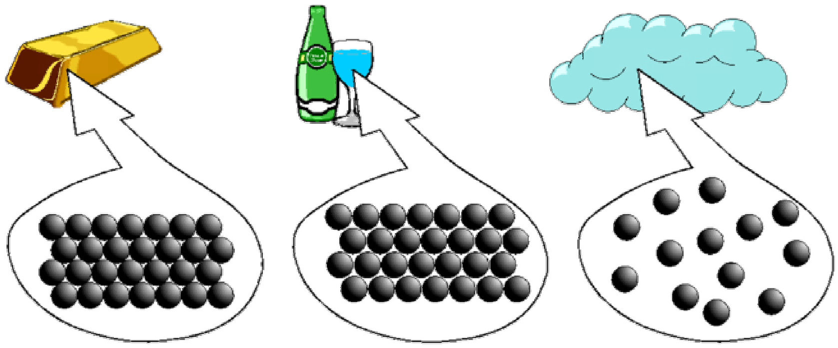

Figure 1: The three state of matter. (Left), Solids where the molecules are fixed and vibrating. (Middle) Liquid where the molecules are still connected to each other but can move around. (Right) Gas where molecules move around at random and only when they hit something do they change direction.

In solids and liquids, the molecules or atoms are very close together, relative to their size, and hence are incompressible and have distinct volume. An analogy for liquid is to imagine a jar of marbles. We can move the marbles aside if we put our hand in the jar but we cannot squash them down. As a result of this incompressibility, liquids and solids do not change volume when pressure is increased and the pressure will be transmitted evenly through the substance (Pascal's Principle). The diver's body, a large percentage of which is made up of liquid and solid, will automatically assume the same pressure as the surrounding environment and is not compressible.

There are also gas spaces in the body and gases are greatly affected by pressure because the distance between the molecules is great in relation to their size. This means gas spaces can be compressed and as a result, the human body's air spaces, such as lungs, ears and sinuses, require attention when diving to avoid discomfort or injury during the dive. An understanding of how these injuries occur is essential for safe, enjoyable diving.

PASCAL PRINCIPLE[4]

Although all matter is compressible under enough pressure, within the pressure ranges encountered by commercial divers, water is considered incompressible for practical purposes. Any outside pressure applied to the surface of water (or other liquid) transfers equally in all directions through the liquid. This is the principle by which a hydraulic lift operates, and is called *Pascal's Principle*.

Because body tissues consist primarily of water, pressure transfers through them directly and equally in all directions, with no direct effect. Hence, the human body can endure the tremendous pressures exerted on it underwater, and the diver only feels the pressure in the body's air spaces.

When discussing the properties of a gas, it is assumed that the gas molecules are in constant motion and, when they strike the surface of a container, an instantaneous pressure results. When the millions of molecules present in even a small volume of gas, strike a surface, a constant pressure is produced.

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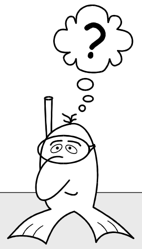
4 Section 1-25, PADI "The Encyclopaedia of Recreational Diving", International PADI 1996, ISBN 1-878663-02-X



NTK!

Knowledge of the properties and behaviours of gases – especially those used for breathing – is of vital importance to a diver!

DIVING GASES

OXYGEN – O_2

This colourless, odourless, tasteless and active "gas" readily combines with other elements. Fire cannot burn without oxygen and man cannot live without oxygen. It can also be a diver's worst enemy.

NITROGEN – N_2

Colourless, odourless and tasteless gas, unlike oxygen it will not support life. Nitrogen in the air is inert and is essentially a carrier gas.

HELIUM – He

Also colourless, odourless and tasteless. It is however monatomic, which means it exists as a single atom in its free state; it is also inert. A rare element first discovered in 1868, since helium is seven times lighter than air, its primary use initially was the inflation of manned balloons. Helium co-exists with natural gas in some wells in the US, Canada and Russia. When mixed with oxygen it is used for diving in excess of 50m since it has no narcotic effect. Helium tremor occurs over 200m.

HYDROGEN – H_2

Hydrogen is diatomic, colourless, odourless and tasteless, and is so active that it is rarely found in its free state on earth. The sun and stars are almost pure hydrogen. Hydrogen is the lightest of all elements, i.e. hydrogen balloons, etc. It is violently explosive when mixed with air, as the flaming crash of the Hindenburg airship illustrated.

CARBON DIOXIDE – CO_2

Colourless, odourless and tasteless, when found in small percentages in air. Greater concentrations have an acid taste and odour. Chemically active, commonly found in soft drink and fire extinguishers because it is non-flammable. Natural by-product of respiration in animals and humans.

CARBON MONOXIDE – CO

A man made gas which is the product of an internal combustion engine. It is highly poisonous to man; colourless, odourless and tasteless. Hence, it is difficult to detect. Carbon monoxide is chemically highly active and seriously interferes with the bloods ability to carry oxygen, forming carboxy-haemoglobin. A typical cause of carbon monoxide poisoning in divers is contamination of the air supply from improper placing of the compressor engine exhaust, close to the pump inlet.

WATER VAPOUR – H_2O

Air always contains some percentage of water vapour, which must be considered as a gas. This "humidity" sometimes makes the weather uncomfortable.

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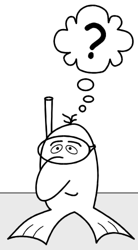
IDEAL GAS LAW[5]

A pressure applied to a gas causes significant changes in gas volume and temperature. In the conventional diving range, the *Ideal Gas Law* reasonably describes this. This is the most used law in diving medicine along with its two derivatives; *Boyle's Law* (Pressure/Volume Relationship) and *Charles's Law* (Pressure Temperature/Relationship).

The ideal gas law states that the product of absolute gas pressure (P) and volume (V) must equal the product of moles of gas (N), the gas constant (R) and the absolute temperature (T).

$$P \times V = N \times R \times T$$

Hey! Don't get carried away. You do not need to know this!



NTK!

Understanding the pressure volume relationship will help you to avoid a number of potential injuries associated with occupational diving.

■ PRESSURE/VOLUME RELATIONSHIP FOR GASES (BOYLE'S LAW)

Boyle's Law states:

✔ **For any gas at a constant temperature, the volume of a given mass of gas will vary inversely with absolute pressure.**

If ten molecules were placed in a rigid container, they would move around randomly, striking the walls, thereby generating a pressure.

Let us define the pressure these 10 molecules create as one unit of pressure.

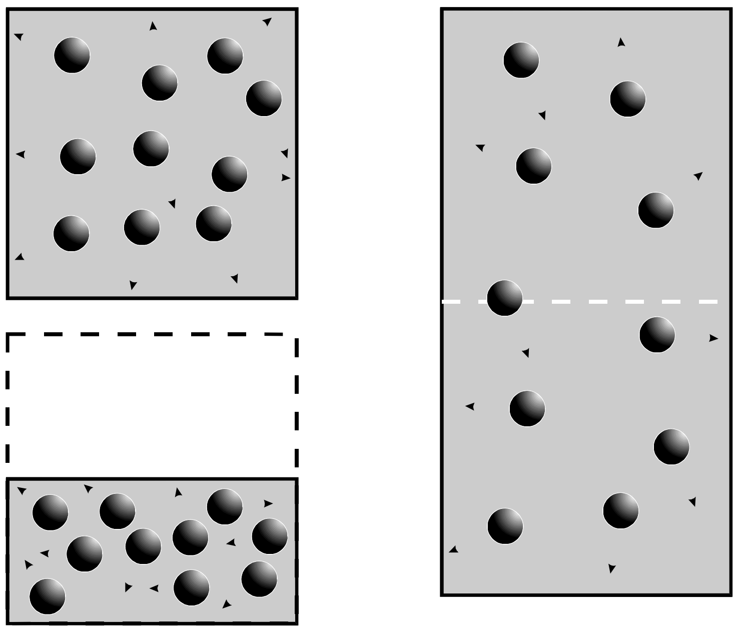


Figure 2: (Top Left): Molecules in a container generating pressure.
Figure 3: (Bottom Left): Volume halved, pressure generated is doubled.
Figure 4: (Right): Volume doubled, pressure generated is halved.

5 Page 56, Diving Medical Technicians Handbook, Dr C.J. Acott, Royal Adelaide Hospital.

In other words, if the volume is halved, the pressure will double. The reverse is also true. If the volume were doubled then the molecules would have twice as much room in which to move. Therefore, the molecules would strike the walls less often. This means only half the pressure will be exerted on the container walls. In other words, if the volume is doubled the pressure is halved.

Generally, if the volume that a gas occupies is increased, the pressure will decrease. This is known as Boyle's Law. If we now consider a flexible container, such as the lungs, the implication of Boyle's Law can readily be seen. When a snorkel diver holds their breath, their lungs contain a volume of air (approximately 6 litres), which will be reduced as they descend because of the increasing water pressure surrounding them.

We know that at ten metres/33 feet (2 atmospheres absolute), the pressure has doubled and we now know that the volume of the lungs at this depth will be halved. As the diver ascends back to the surface the pressure will decrease and the volume of the lungs will increase again.

All other gas spaces within the body can be expected to do the same as the lungs. However, in the case of the middle ear, volume expansion or reduction cannot be tolerated because this gas space is surrounded by non-flexible bone. Ambient pressure air needs to be introduced into the middle ear, via the Eustachian tube, to avoid damage.

As the extent of volume change is dependent upon pressure changes, it can be seen that the major area for concern is in the top ten metres of the water column. When ascending from 10 metres/33 feet to the surface the pressure is halved. This results in the volume of air doubling. Applying these same principles and comparing the reduction to that experienced when travelling from the surface to 10 metres, with that experienced from 30 metres/99 feet to 40 metres/132 feet, the volume change is only twenty-five per cent.

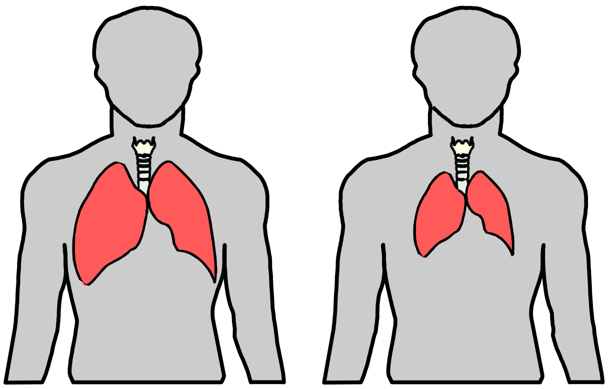
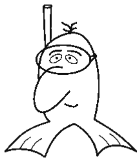


Figure 5: The lungs are a flexible container. (Left) Lungs at 1 ATA. (Right) Lungs at 10 metres or 2 ATA.

It is therefore likely that most cases of pressure related injury (barotrauma) would occur within the top ten metres/33 feet of water, and this is found to be the case. An understanding of Boyle's Law is essential, as it relates to many areas in diving not only to barotrauma but also to loss of buoyancy due to wetsuit compression. Increased air consumption and increased air density at depth are also based on the pressure/volume relationship.

BOYLES LAW[6]

The law, which governs the relationship between pressure and volume, is known as Boyle's Law, which states that provided the temperature remains constant, the volume of a fixed amount of a gas will vary inversely with the absolute pressure of that gas. This law can be stated using a formula $P \propto \frac{1}{V}$ and simply stated, means that as pressure increases, the volume of a given amount of gas will decrease. Gases behave in this manner and it can be determined that pressure x volume equals a constant figure, that is P x V = Constant. Therefore $P_1 \times V_1 = P_2 \times V_2$. Using this equation, any changes to pressure or volume can be determined.



NOTE: Any calculations involving Boyle's Law must be done using *absolute pressures*.

ADAS COMPETENCY

Demonstrate an understanding of the effects of pressure, volume and temperature changes on the diver and their implications.

Explain how Charles' law applies to cylinder pressures.

THE PRESSURE/TEMPERATURE RELATIONSHIP (CHARLES LAW) [7]

The relationship between pressure and temperature is expressed by Charles' Law. Charles' law states;

✔ **That for a fixed amount of gas at a constant pressure, the Volume of the gas will vary directly with the absolute temperature. Alternatively, for a fixed amount of gas at a constant volume, the *Pressure* of the gas will vary directly with the absolute temperature.** This law is expressed mathematically as:

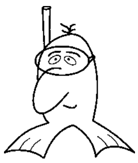
$$\frac{V}{T} = \text{Constant}$$

Alternatively, as:

$$\frac{P}{T} = \text{Constant}$$

For any calculations involving Charles' Law, all workings must use Absolute Temperature.

NOTE



That the scuba cylinder is a non-flexible, constant volume container. As kinetic energy increases with increased temperature, the molecules travel faster. They hit the vessel walls harder and more often. This means pressure within the cylinder increases as the temperature is raised, and there is an increase in pressure associated with heating a scuba cylinder. To prevent this increase in pressure (and possible rupture of the scuba valve safety disc), it is especially important to store full scuba cylinders in a cool place.

ABSOLUTE TEMPERATURE

When temperature is measured on a number line, the freezing and boiling points of water appear as part of a continuing scale. It should be obvious however, that the freezing point of water measured in degrees Celsius or degrees Fahrenheit is not the beginning of the number line for temperature.

Temperature can be reduced to an absolute zero point, which is practically impossible to reach.

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6 NASDS text “Search and Recovery Diver, Second Edition, 1995, ISBN 1 875 355 04 9

7 This section taken from the NASDS text “Search & Recovery Diver, Second Edition, 1995, ISBN 1 875 355 04 9

Both number lines are the same but use a different sized unit. The metric unit is degrees Celsius for which absolute zero is minus 273°. When converting degrees Celsius to absolute temperature they are called Kelvin after an eminent Scottish physicist called Lord Kelvin.

To convert degrees Celsius to absolute temperature (Kelvin) add 273°.

NON IDEAL GAS AND VAN DER WAAL'S EQUATION[8]

At high pressures and low temperatures, gases no longer obey the gas laws of Boyle and Charles. A gas, which obeys these laws, is an Ideal Gas and assumes that the gas molecules exert no influence on each other and hence the gases are perfectly compressible. This is a reasonable *assumption* for conventional diving depths, but as gas molecules come closer together during compression, they begin to exert considerable force on each other. For example at 600msw (61 bar) gases are about 8% less compressible than would be predicted from the Ideal gas law. In addition to these inter molecular forces the actual volume of the gas molecules is important as well; as the gas volume decreases with an increased pressure the total volume of the molecules becomes an appreciable part of the total volume of the gas. These molecules make more impacts on the wall of the vessel per unit time.

Hydrogen and Helium are less compressible and are called *"over perfect* gases", while nitrogen and carbon dioxide are more compressible and are called *"under perfect gas".* In these circumstances, Van der Waal's equation describes the behaviour of these gases under increased pressure.

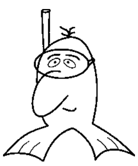
$$P(V-b) = NRT$$

(b is an empirical constant representing the correction for the space occupied by the molecules and can be found in handbooks of chemistry and physics).

Now we only put this in to really confuse you!

THE COMBINED GAS EQUATION[9]

Boyle's Law and Charles' Law deal with the three principles of pressure, temperature and volume. They can be linked to give the combined gas equation.



This equation is represented as: $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ where P_1 is initial pressure, P_2 is final pressure, V_1 is initial volume, V_2 is final volume, T_1 is initial temperature and T_2 is final temperature.

The basis of using this equation is that for any given temperature, pressure or volume, the quotient $\frac{PV}{T}$ will be constant. Therefore, if any of the three factors change, at least one or both of the other factors will change accordingly to maintain the value of the constant. In other words, the quotient of the new temperature, pressure or volume must equal the same constant.

The advantage of this formula is that any one of the three variables can be determined simply by using that part of the formula required.

8 Page 58, Diving Medical Technicians Handbook, Dr C.J. Acott, Royal Adelaide Hospital.

9 From the NASDS text "Search and Recovery Diver, Second Edition, 1995, ISBN 1 875 355 04 9

ADAS COMPETENCY

Demonstrate an understanding of partial pressure and solubility of gases and their effect on the diver.

Define the terms:

- ✔ **Partial pressure**
- ✔ **Diffusion**
- ✔ **Saturation**
- ✔ **Desaturation**
- ✔ **Equilibrium**

Explain the principles of partial pressure of gases (Dalton's Law).

Calculate partial pressure of gases at different depths.

Explain the principles of solubility of gases (Henry's Law).

Explain the need for decompression as it relates to partial pressure and solubility of gases.

PARTIAL PRESSURES (DALTON'S LAW)

Dalton's Law states:

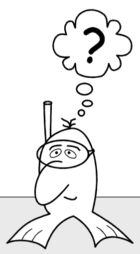
✔ **The total pressure exerted by a mixture of gases is equal to the sum of the pressures of each of the different gases making up the mixture – each gas acting as if it alone was present and occupied the total volume.**

Air is a mixture of gases with the two main constituents being oxygen, O_2, approximately 20% or 1/5, and nitrogen, N_2, approximately 80% or 4/5.

Let us imagine we have a rigid container which has 10 molecules of gas and the random movement of these molecules is striking the walls of the container combining to create a pressure which we call one unit, e.g. total pressure = 1 ATA. If the 10 molecules of gas are made up of oxygen and nitrogen in the above proportions, then two molecules are oxygen and eight are nitrogen.

If the eight nitrogen molecules were removed then the pressure would only result from the two molecules of oxygen left. The container still has the same volume but only 20% (1/5) of the original ten molecules will strike the walls of the container. Therefore, the pressure created from the oxygen alone is 20% (1/5) of the original total pressure. If the eight nitrogen molecules are replaced and the oxygen molecules removed, the pressure due to nitrogen alone will be 80% (1/5) of the total pressure as there are now 8 out of 10 molecules striking the walls of the container.

If the total pressure is one unit, the pressure due to oxygen will be 20% or 1/5 of one unit, i.e. 0.2 units and the pressure due to nitrogen will be 80% or 1/5 of one unit, i.e. 0.8 units. In other words, in a gas mixture such as air the gases act independently of each other. They each produce only part of the total pressure. This part is known as partial pressure (Pp). The partial pressures always add up to give total pressure. This is Dalton's Law. In the example above, the partial pressure of oxygen (PpO_2) plus the partial pressure of nitrogen (PpN_2) equals the total pressure of air (TP air).



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This law helps to explain how the gases we breathe on the surface can start to affect us differently when we breathe them underwater.

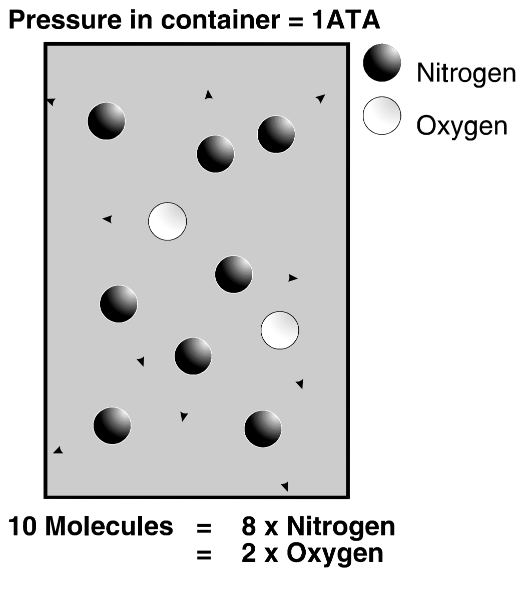
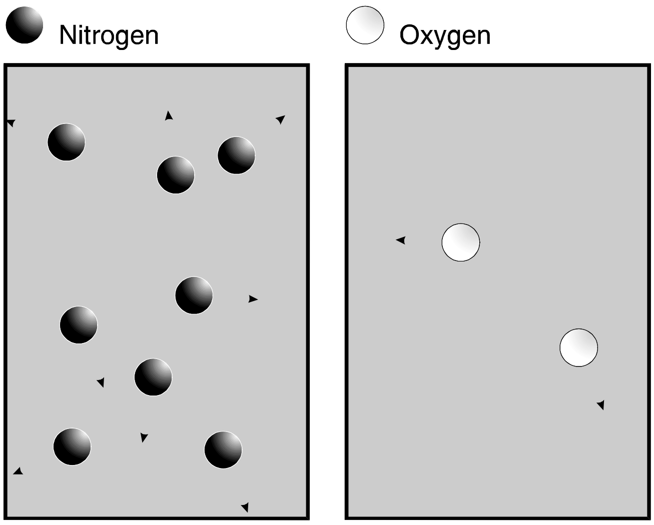


Figure 6: A rigid container which has 10 molecules of gas and the random movement of these molecules is striking the walls of the container combining to create a pressure which we call one unit, eg total pressure = 1 ATA.



If the oxygen molecules are removed the pressure will be 80%

80% x 1 ATA = 0.8 ATA

If the nitrogen molecules are removed the pressure will only be 20%

20% x 1 ATA = 0.2 ATA

Figure 7: A rigid container, which has had the constituent gases separated.

If the eight nitrogen molecules were removed then the pressure would only result from the two molecules of oxygen left. The container still has the same volume but only 20% (1/5) of the original ten molecules will strike the walls of the container. Therefore, the pressure created from the oxygen alone is 20% (1/5) of the original total pressure. If the eight nitrogen molecules are replaced and the oxygen molecules removed, the pressure due to nitrogen alone will be 80% (1/5) of the total pressure as there are now 8 out of 10 molecules striking the walls of the container.

If the total pressure is one unit, the pressure due to oxygen will be 20% or 1/5 of one unit, i.e. 0.2 units and the pressure due to nitrogen will be 80% or 1/5 of one unit, i.e. 0.8 units. In other words, in a gas mixture such as air the gases act independently of each other. They each produce only part of the total pressure. This part is known as partial pressure (Pp). The partial pressures always add up to give total pressure. This is Dalton's Law. In the example above, the partial pressure of oxygen (PpO_2) plus the partial pressure of nitrogen (PpN_2) equals the total pressure of air (TP air).

TP air	=	$PpO_2 + PpN_2$
(T) = or	=	0.2 + 0.8 = 1.0

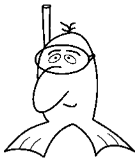
When air at one atmosphere absolute (1 ATA) or sea level is now considered, it can be seen that:

TP air	=	$PpO_2 + PpN_2$ = 1 ATA

If the total pressure in our lungs is now doubled, for example by diving to 10 metres/33 feet, the percentage of each gas will remain the same but the partial pressures will double, i.e. total pressure at 10 metres/33 feet = 2 ATA.

The partial pressure of oxygen is equal to 20% or 1/5 x 2 = 0.4 ATA.

As the overall pressure increases, the partial pressures of constituent gases also increase.



It is important to understand that it is the partial pressure of a gas that is relevant physiologically, not its percentage. For example, in air at 40 metres/132 feet the total pressure is 5 ATA, which means the percentage of oxygen in the air is 20% (or one fifth of 5). Therefore, the partial pressure of oxygen is 1 atmosphere.

When we dive we will be breathing different partial pressures of gases and we need to be aware of diving ailments which may result because of this, such as oxygen poisoning, nitrogen narcosis, hypoxia, carbon monoxide poisoning and carbon dioxide poisoning. To understand Dalton's Law will also help in understanding the cause of decompression illness.

GAS DIFFUSION

The movement of gas molecules is very random and, given sufficient time, they will eventually spread out evenly to completely occupy the container that confines them. An example often experienced is of a bottle of perfume being opened in a closed room. The scent can rapidly be detected in all parts of the room as the molecules achieve even distribution.

This movement of molecules is referred to as diffusion. If two different gases were placed on either side of a perforated partition then they would eventually intermingle. However, the molecules do not travel at the same rate. The rate of diffusion depends on the weight of the molecule. The heavier the molecule, the slower it travels.

If we consider a bubble of nitrogen within a medium rich in oxygen, such as a nitrogen bubble in blood rich in oxygen, then the nitrogen, which is lighter than oxygen, will diffuse from the bubble and thus it will decrease in volume. This is one of the reasons why pure oxygen is administered to divers suffering from decompression illness or pulmonary barotrauma.

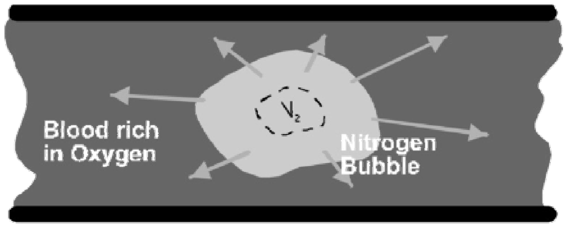
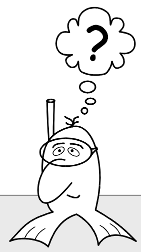


Figure 8: Gas diffusion. Nitrogen, which is lighter than Oxygen, diffuses out of the bubble faster than the heavier Oxygen can diffuse into it.



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Understanding gas solubility will help you to understand how to avoid decompression illness, one of the major hazards associated with diving.

GAS SOLUBILITY IN LIQUIDS (HENRY'S LAW)

Henry's Law states:

✔ **That 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.**

Gas diffusion does not only occur in air. Gases also diffuse into and out of liquids. This process, more commonly termed dissolving, is usually applied to solids dissolving in a liquid. A similar process allows gases to diffuse into a liquid. The net result is the same. Given sufficient time, a gas will diffuse into a liquid to a point where equilibrium or saturation occurs. That is, the amount of gas going into the liquid will equal the amount of gas leaving the liquid.

Conversely, when the partial pressure of a gas over a liquid drops, the amount of molecules coming out of solution will exceed the number going in. Therefore, a new equilibrium will be achieved after a period of time.

However, if the pressure drop is too rapid, molecules will come out off solution so rapidly that they form bubbles within the solution.

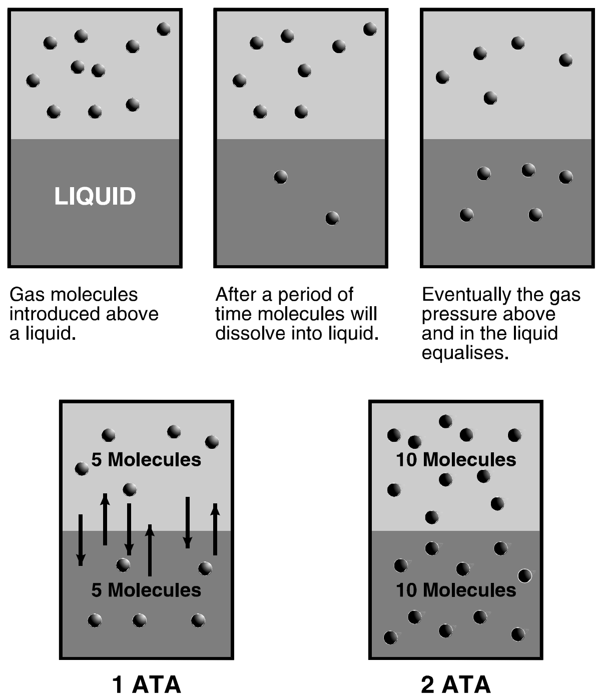


Figure 9: Gas diffusion.

This process can also occur in the human body. The lungs act as the gas space and the tissues of the body will receive the dissolved gases via the blood. The time for equilibrium to be achieved will depend on the solubility of the gas in the particular type of tissue and the rate at which the gas is supplied to the tissue via the blood stream.

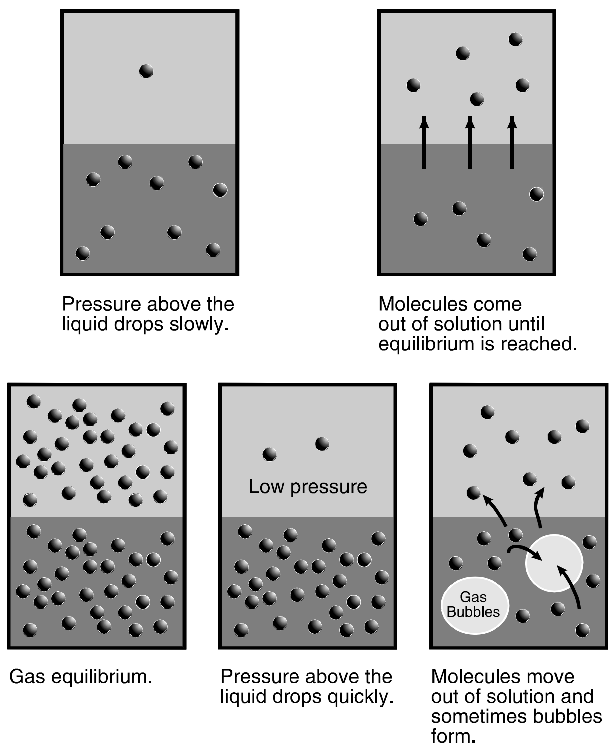


Figure 10: Gas diffusion.

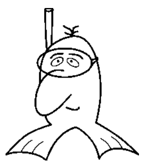
As a diver descends, the air they breathe is at a higher pressure; therefore, gases dissolve in the tissues until a new equilibrium is reached. This new equilibrium may take 24 hours or longer to be reached, depending upon the tissue. For instance, blood will achieve a new equilibrium almost instantaneously while bone tissue, because of its poor blood supply, will take up to 24 hours to reach complete saturation (equilibrate).

As a diver surfaces, the partial pressures of the gases they breathe decrease and dissolved gases move out of the tissues until equilibrium is reached. The movement of gases out of the tissues is called desaturation. Blood will become de-saturated rather rapidly while bone tissue will take a long time.

If a large amount of gas dissolves over a period of time, then a similar period of time is required to eliminate the gas from the tissues. If insufficient time is allowed, then the dissolved gas will come out of solution as bubbles. This principle can be demonstrated readily when the top of a soft drink can is opened. Gas, in this case carbon dioxide, has been held in solution by the pressure in the gas space between the liquid and the ring- pull. Once the ring-pull is opened, the amount of gas dissolved is too great to diffuse passively from the solution so bubbles form instead.

Whenever a quantity of gas has been dissolved in a diver's body, whatever depth or pressure, it will remain in solution as long as the pressure is maintained. However, as the diver starts to ascend towards the surface, more and more of the dissolved gas will come out of solution. If the rate of ascent is controlled; through the use of decompression tables; the dissolved gas will be carried to the lungs and exhaled before it accumulates sufficiently to form bubbles in the tissues. If, on the other hand, the diver rises suddenly and the surrounding pressure is reduced, at a rate higher than the body can accommodate, bubbles may form and become trapped in the small blood vessels causing pain in the area of the joints. The associated pain and discomfort of decompression sickness is treated by re-pressurisation to resolve the bubbles followed by slow decompression using special tables.

MIXED GAS AND REBREATHING APPARATUS



The use of mixed gas and rebreathing apparatus is a way of overcoming some of the limitations of air diving. Mixed gas diving is a direct application of Henry's Law, which states that the mass of gas absorbed depends on the partial pressure of the gas. By reducing the amount of nitrogen in the gas, you reduce the partial pressure of nitrogen compared to what it would be at the same depth if using air. This reduces the amount of nitrogen absorbed and increases the safety margin.

Rebreathing apparatus are simply based on the physiological fact that the human lungs cannot absorb all the available oxygen in the air, which means that there is a significant amount of oxygen left in the expired air. An open circuit system simply wastes this oxygen, whereas a closed circuit rebreathing device utilises the available oxygen by recycling the expired air. This extends bottom time significantly.

There is more information on mixed gas and rebreathing apparatus in the chapter on plant, equipment and maintenance procedures.

3 CHAPTER 3 – BUOYANCY, LIGHT, SOUND AND THERMAL CONDUCTIVITY

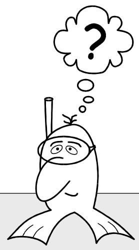
INTRODUCTION

Issues of buoyancy, light, sound and thermal conductivity all affect the diver underwater. You will need to:

✔ know the principles of buoyancy and how it affects both the diver and lifting tasks, and

✔ know the principles of thermal conductivity and the behaviour of light and sound and how these affect the diver.

We will look at specific risk controls for these areas in the chapter on managing risk.



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The understanding of the concepts of buoyancy is the key to the success or otherwise of all diving operations.

BUOYANCY AND ARCHIMEDES' PRINCIPLE

BUOYANCY

A thorough understanding of the principle of buoyancy is necessary to ensure safe, comfortable diving. During a dive, many factors can affect a diver's state of buoyancy. These factors are usually controlled either with the use of a buoyancy jacket or by controlling depth of breathing.

Factors that influence the buoyancy of a diver during a dive include:

✔ wetsuit compression,

✔ depth of breathing,

✔ volume of air left in a cylinder or the type of cylinder, and

✔ carrying objects while underwater.

STATES OF BUOYANCY

The buoyancy of an object can be described as one of three states:

✔ positive or floating

First Edition — December 2003; Revision (0)

REVISED BY: Active Learning Partners (Bronwen Campbell), Ian A. Milliner, and Paul Bulter **DATE & TIME:** 24-Feb-05 10:00
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ADAS REF: This Section corresponds to Module 6.3, Diving physics, physiology and associated calculations.

- ✔ negative or sinking
- ✔ neutral - neither floating nor sinking

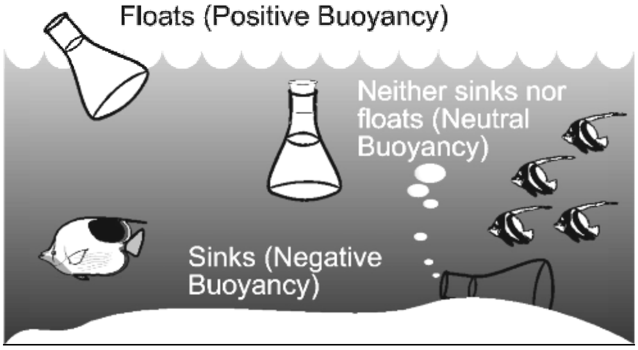

Figure 11: States of Buoyancy

The ideal state of buoyancy during a dive is to be neutral. The human body is close to being neutrally buoyant. Slight variations in breathing will determine how much of the body protrudes above the water. At the start or end of the dive, positive buoyancy is preferred to enable the diver to relax on the surface. Negative buoyancy is useful when working, diving in swell or to "anchor" you on the bottom, to take a photograph for instance. Therefore, we want to be able to control our buoyancy.

With careful practise, it is possible to attain a state of neutral buoyancy where the body neither floats nor sinks.

ADAS COMPETENCY

Demonstrate an understanding of buoyancy and the Archimedes' Principle.

Explain Archimedes' Principle.

Explain the different effects of salt water and fresh water on buoyancy.

Calculate the buoyancies of various objects at different depths.

Define positive, negative and neutral buoyancy.

Describe equipment used to compensate for buoyancy changes.

ARCHIMEDES' PRINCIPLE

Many hundreds of years ago, a Greek gentleman by the name of Archimedes leapt into his overfull bath and made an epic discovery.

This is roughly how the law, which governs the state of buoyancy, came to be known as Archimedes' Principle. This principle applies to the buoyant or upward force, which is experienced by all objects placed in a liquid.

If an object is placed in a container that is totally filled with water, it is obvious that some water will spill out or be displaced.

Objects placed in a liquid will displace an amount of liquid equal to the volume of the object immersed.

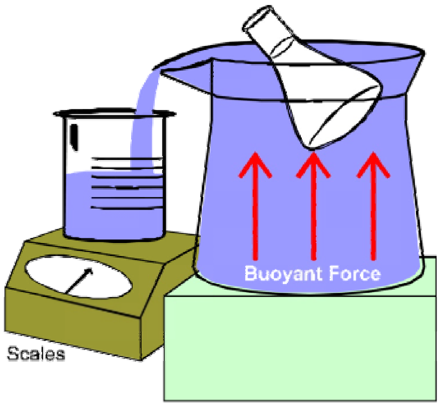

Figure 12: Objects placed in a fluid displace some of that fluid. The weight of water displaced equals the upward lift or buoyant force given to the bottle.

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ADAS REF: This Section corresponds to Module 6.3, Diving physics, physiology and associated calculations.

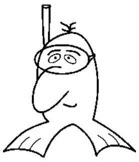
If the object is weighed before being placed in the liquid, then again while in the fluid filled container, a loss of weight will be recorded.

While the object is in the fluid it appears to weightless. This is known as the Apparent Weight. The difference between the actual weight of the object and the apparent weight is equal to the weight of the fluid displaced.

The apparent weight is the difference between the actual weight of the object due to gravitational forces and the buoyancy force. In a fluid an object has two forces acting on it, they are:

✔ Downward force, due to gravity; actual weight

✔ Upward; buoyant force



ARCHIMEDES' PRINCIPLE STATES:

✔ **An object immersed in a liquid will displace an amount of liquid equal to the volume of the immersed object, and any object wholly or partially immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.**

An object will float when the buoyant force or upward force is greater than the actual weight. That is, the volume of fluid displaced must weigh more than the actual weight of the object. Generally large volume, lightweight objects float.

In order for an object to sink, the buoyant force must be less than the actual weight. That is, the volume of fluid displaced weighs less than the actual weight of the object. Generally small volume, heavyweight objects sink.

The human body normally floats when the lungs are full. However, when air is expelled the volume of the chest decreases, the volume of water displaced reduces, and the body sinks.

It should be noted that the weight of fluid displaced is dependent upon the density of the fluid.

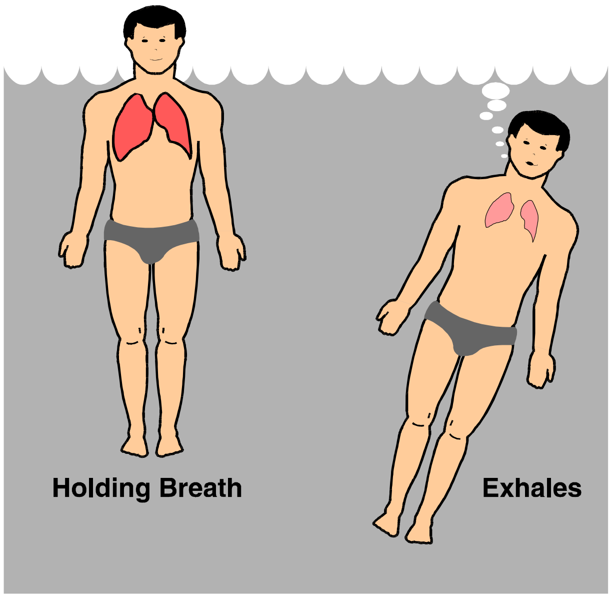


Figure 13: When air is expelled the volume of the chest decreases, the volume of water displaced reduces, and the body sinks.

Fresh water has a density of 1.000 gram per cubic centimetre (1.000g/cm^3), compared with seawater which is 1.025g/cm^3. If an object displaces 1 litre of fresh water, the water will weigh 1 kilogram. If 1 litre of salt water is displaced it will weigh 1.025 kilograms.

If the object is placed in fresh water, the buoyant force (uplift) will be less than if placed in salt water, as the buoyant force is equal to the weight of the water displaced not the volume.

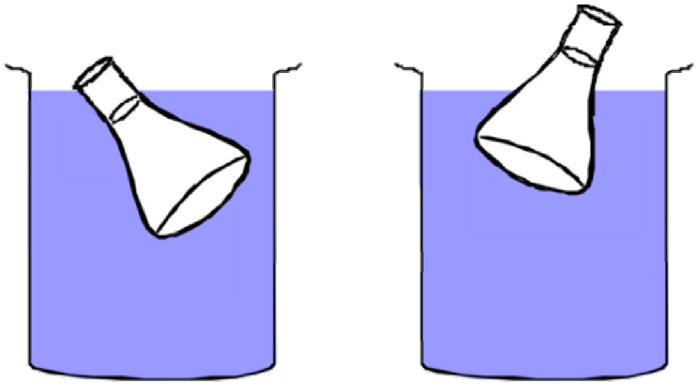


Figure 14: An object is less buoyant in fresh water (Left) Fresh water – less buoyant (Right) Salt water – more buoyant)

EXAMPLE

An object displaces a volume of five (5) litres. What will the buoyancy force be?

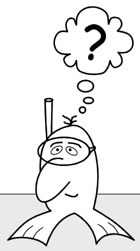
(a) In fresh water?

(b) In salt water?

Solution

(a) In fresh water the density of fresh water is 1.000g/cm^3. Therefore, the buoyant force will be (volume displaced x the density of the fluid), i.e. (5 litres x 1.000) = 5 kilograms uplift.

(b) In salt water the density of salt water is 1.025g/cm^3. Therefore, the buoyancy force will be (volume displaced x the density of the fluid), i.e. (5 litres x 1.025) = 5.125 kilograms uplift.



CALCULATIONS ASSOCIATED WITH BUOYANCY

> **NTK!**
>
> Being able to calculate the buoyancy of an object can help with the work you may be undertaking as an occupational diver.

Once the buoyant force has been calculated, the next step is to incorporate the concept of apparent weight. As has already been seen, the apparent weight is the difference between the actual or gravitational weight of the object and the buoyant force created by the fluid into which the object is placed. For example, if an object has an actual weight of 1,000 kilograms and when placed in a liquid it displaces 100 litres, the displaced fluid will cause an uplift or buoyant force reducing the actual weight to a reduced weight or apparent weight.

If the weight of the fluid displaced is calculated, this figure can be taken from the original or actual weight of the object to give an apparent weight.

EXAMPLE

A mooring clump weighing 1000 kilograms displaces 100 litres of fresh water. What will be his apparent weight while in the water?

Solution

List all relevant information.

✔ Mooring Clump; Gravitational (downward) force (GF) = actual weight = 1000kg

✔ Volume of water displaced = 100 litres as this is fresh water

✔ Weight of water displaced = 100kg so giving 100kg uplift

✔ Therefore buoyant force = 100kg uplift

Subtract the buoyant force (or upward force) from the actual weight (gravitational or downward force) to determine the apparent weight.

✔ (Actual weight - buoyant force) = apparent weight

✔ (1000kg - 100kg) = 900kg

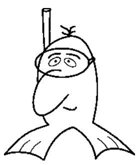
✔ Therefore the apparent weight = 900kg

The mooring clump appears to weigh 900kg only, whilst immersed in the liquid.

Once the apparent weight of something has been calculated, this figure should be used for any future buoyancy calculations. The apparent weight is what must be overcome if the object is to be lifted to the surface.

■ CALCULATING AIR REQUIRED TO LIFT AN OBJECT

In order to calculate the amount of air required to lift an object to the surface several factors must be determined if possible. They are:



✔ Actual weight of object

✔ Volume of object

✔ Weight of the fluid displaced

✔ Apparent weight of object

✔ Depth of object

The Actual Weight of the Object is not always easy to determine. By first determining the material from which it is constructed, and then using its approximate volume, a rough estimate can be made using the concept of specific gravity (SG).

For example, if an object is made from steel and has an approximate volume of 1 cubic metre then, by using the SG of steel, the weight will be equivalent to the volume multiplied by the SG, i.e. 1 cubic metre (1000 litres) x SG = total weight in kilograms.

This is usually only an approximation but at least will give a guide to the weight to be dealt with.

Volume of the Object can also be difficult to determine. For regular shaped objects, simple formulae are available. However, if the object is irregular in shape, it may be necessary to approximate its volume by dividing it into areas that resemble cylinders, squares, triangles

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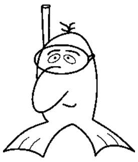
etc. As with actual weight, the result may only be an approximation, but it will at least give a guide.

The Fluid Displaced will be directly related to the volume of the object. The weight of the fluid can be calculated simply by using the specific gravity. Most recovery work is carried out in either fresh or salt water and so a figure of 1.000g/cm^3 for fresh water and 1.025g/cm^3 for salt water should be used. Various instruments are available for determining the SG of a fluid and are termed hydrometers. You may have seen a hydrometer used to test the salinity of an aquarium.

Calculating The Apparent Weight of an object has been discussed previously. The actual weight of the object minus the weight of the fluid displaced, will give the apparent weight.

The Depth of Water in which the object lies will determine the amount of air required to be pumped, or brought from the surface, in order to inflate whatever lifting devices are used.

The correct procedure for approaching a lift calculation is:



- ✔ **Step 1** Draw a simple diagram
- ✔ **Step 2** List all relevant information
- ✔ **Step 3** Draw and calculate upward and downward forces involved
- ✔ **Step 4** Calculate apparent weight
- ✔ **Step 5** Calculate volume of air required to raise object

Calculations that are more detailed can be found in Section 3, Chapter 4.

■ DIVING EQUIPMENT USED TO COMPENSATE FOR BUOYANCY CHANGES

A diver can vary buoyancy in several ways. By adding weights to the equipment, the diver can sink. If wearing surface-supplied diving dress, the diver can increase or decrease the amount of air in the suit, thus changing the displacement and thereby the buoyancy. Minor changes in the volume can produce a significant change in buoyancy. Buoyancy compensators are also able to change buoyancy.

THERMAL CONDUCTIVITY, LIGHT AND SOUND UNDERWATER

Thermal conductivity in water is far greater than in air. This means that the heat transfer rate from the diver is increased and the diver is at greater risk of hypothermia in the water.

Light is reflected, refracted and absorbed in water. This affects visibility, colour and distance perception. The red end of the light spectrum is absorbed first and the blue end last. Underwater videos or cameras may use a red filter to restore colour.

Sound travels at a far greater speed in water than in air. This has two effects. One is that sounds appear louder in water and the second is that it is far more difficult for a diver to locate the source of the sound.

This has safety implications which the dive supervisor needs to address in the planning stage.

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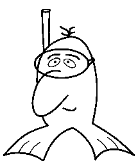
4 CHAPTER 4 – CALCULATIONS

INTRODUCTION

GENERAL

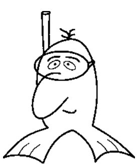
Depending on the complexity of the dive operation, planning may include calculations of things such as:



- ✔ Breathing gas requirements
- ✔ Time available for working underwater
- ✔ Compressor gas delivery
- ✔ Temperature effects
- ✔ Buoyancy/lifting
- ✔ Gas mixing
- ✔ Partial pressures in chambers and bells
- ✔ Soda lime use (for rebreathers)
- ✔ Temperature of water for hot water suits

You need to make sure you are using the correct units in your calculations. If the answer makes no sense at all, check that you are using the correct units.

It is also good practice to have an estimate of the magnitude of the answer. By doing this, you can quickly see if you have missed a decimal point, or mis-keyed. If you are expecting an answer between 1 and 10 and you get and answer in the hundreds, you have probably missed a decimal point.



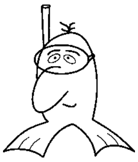
Remember: Always have an idea of what the answer should be when using a calculator – it is easy to mis-key.

CALCULATION TIPS AND CONVERSIONS

The other system in use is the Imperial or FPS (Foot, Pound, Second) system. This is used by American companies and those using the US Navy tables. The next sections cover some examples of the calculations you are likely to need in planning the dive operation.

Some fundamentals to remember when performing calculations:

- ✔ All units must be from the same system, or converted to the appropriate unit for that system. In other words, if you have the breathing rate in cubic feet per minute, but you have the volume of the cylinder in cubic metres, you will need to convert from cubic feet to cubic metres before performing the calculation.



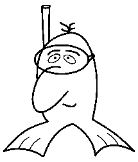
✔ Make sure you get the conversion around the right way. The best way is to write it down with the units and make sure that the equation has the units cancelling each other out to give you the final unit you want. To convert from cubic feet to cubic metres, multiply by 0.028317. You would write this down as:

☞ $1.236ft^3 \times 0.028317m^3 = 0.035m^3$

✔ To convert this from m^3 to litres, you would write it as follows:

☞ $0.035m^3 \times 1000$ litres = 35 litres

☞ If you are converting from cubic metres to cubic feet, you will need to divide by 0.028317



✔ To convert from nautical miles (n mile) to kilometres (km) 1 n mile = 1.852 km. Another commonly used nautical term is a knot (kn). 1 kn = 1 n mile/hour

✔ To calculate the pressure at a given depth, you will need to know how to convert the depth to a pressure. 10 msw = 1 bar. There is also an atmospheric pressure of 1 bar at the surface.

☞ 3 bar = (20 m x 1bar/10m) + 1 bar

☞ **Note**: The units are consistent. In other words, the metres cancel each other out, leaving only bar on both sides of the equation.

Pressure can be expressed using a number of different units. The table on page DS3-9 shows some of the units in use throughout the world and conversion factors for these units.

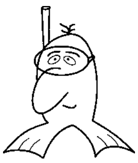
Remember: Do not mix units!

BREATHING GAS CALCULATIONS

The supply of air required for adequate ventilation of the lungs of a working diver can be calculated in advance, based on a general knowledge of the anticipated work-rate, the type of apparatus being used, and the breathing supply.

Typically a working diver would use breathing gas at around 30 - 35 litres/minute. In an emergency or in strenuous work, this is likely to rise and could be as high as 80 litres/minute. The following worked examples are based on 35 litres/minute, but it is also common to use 30 litres/minute.

Gas volumes are measured at surface pressure and are termed free gas volume. In other words, if diver is said to consume 35 litres/minute, this is the volume he or she would consume at the surface, where the pressure is 1 bar.



■ GAS CONSUMPTION FORMULA

✔ Gas consumption = Absolute pressure x Respiratory Minute Volume (RMV)

✔ Absolute pressure (bar) = Depth (msw) ÷ 10 (m/bar) + 1 (bar)

WORKED EXAMPLE - GAS CONSUMPTION

Worked example

What is the gas consumption rate for a diver working at 20 msw, assuming a Respiratory Minute Volume (RMV) at the surface of 35 l/min?

Solution

If the diver is 20 metres below the surface, the absolute pressure is 3 bar. (10m of seawater exerts a pressure of 1 bar, so 20m of seawater is exerting 2 bar, plus atmospheric pressure of 1 bar gives 3 bar absolute pressure).

Since the gas volume at 3 bar is 1/3 of its surface volume, the diver will need 3 times as much gas to properly ventilate his or her lungs.

At this depth, the free gas volume being consumed is 3 x 35 litres/minute = 105 litres/minute.

■ FREE GAS VOLUME FORMULA

The air supply required can be calculated based on expected time in the water, the depth and the maximum breathing rate anticipated.

For scuba, the air supply is limited by the scuba cylinder size and pressure rating. A typical scuba cylinder holds a free gas volume of about 2,500 litres (2.5 m^3) when full. The free gas volume in any gas cylinder is calculated using the water capacity multiplied by the pressure.

✔ Free gas volume = water capacity x pressure.

WORKED EXAMPLE – FREE GAS VOLUME SCUBA

Worked example

A scuba cylinder has a water capacity of 15.1 kg stamped on it. The fill pressure is 150 bar.

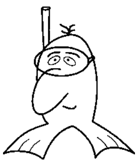
What is the free gas volume?

Solution

Free gas volume (litres at 1 bar) = water capacity (l) x pressure (bar)

Free gas volume (litres at 1 bar) = 15.1 l x (150+1) bar = **2,280 litres**

■ GAS AVAILABLE FORMULA



A simple calculation for how long a diver can work with the scuba cylinder is based on the available gas supply and the consumption rate.

In reality, the gas available is not the full free gas volume in the cylinder, as there must always be a margin of safety to account for a higher breathing rate, gas used for flushing or filling a vest and also to account for any small errors in the pressure gauges. This might be 20 – 25% depending on the company procedures.

✔ Available gas volume = Volume when full x available pressure/pressure when full

WORKED EXAMPLE – AVAILABLE GAS VOLUME SCUBA

Worked example

What is the available pressure for a scuba cylinder filled to 180 bar being used by a diver at 20msw, with a demand valve pressure drop of 10 bar? Assume a safety margin of 20%.

What is the available gas volume, assuming that the volume when full is 2733 l?

Available pressure	= ((180 bar – 3 bar) – 10 bar) x (100% - 20%)
	= 133.6 bar
Available gas volume	= 2733 l x 133.6/181
	= 2017 litres

■ TIME AVAILABLE FORMULA

Time available = Gas Available/Gas consumption

WORKED EXAMPLE – TIME AVAILABLE SCUBA

Worked example

If a scuba diver wants to retain 25% of his or her air as a safety margin, how much time would he or she have at 15 metres? Assume a breathing rate of 30 l/min, a scuba cylinder filled to 150 bar gauge pressure and with 15.1 kg water capacity.

Solution

Gas consumption	= absolute pressure (bar) x breathing rate
	= (1.5 bar + 1 bar) x 30 l/min
	= 75 l/min
Available gas volume	= (15.1kg x 151 bar) x 75%
	= 1710 litres
Time available	= 1710 litres / 75 l/min
	= **22.8 minutes**

■ SURFACE SUPPLY TIME AND GAS AVAILABLE

For surface supply, it is possible to use either a rack of gas bottles (quad) or a compressor to supply breathing gas. Bottled gas is usually supplied in gas racks or quads. A quad may consist of anything from 16 x 50 litre bottles to 64 x 50 litre bottles.

In the case of a quad, the full pressure of the bottle is not available to the diver. This is due to the pressure underwater where the diver is working, the pressure drop across the demand valve and the safety factor selected by the dive supervisor.

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WORKED EXAMPLE – TIME AVAILABLE SSBA USING CYLINDERS

Worked example

For example, a diver is working at 100msw, breathing from a quad at a pressure of 100 bar.

How much time does he or she have, based on available breathing gas?

Solution

At that depth, the pressure is 11 bar. The quad needs to be at a higher pressure than the pressure at the working depth plus any pressure drops in the line (valves etc). In other words, there needs to be a pressure differential for any gas to flow.

It takes say 10 bar to drive the demand valve. Add this to the working pressure of 11 bar. In total, 21 bar is not available to supply to the diver (that is, if the quad pressure dropped to 21 bar, no gas would flow, as there is no pressure differential).

In addition to this, the dive supervisor should allow a margin of error. This means that the quad would be changed over at a higher pressure to avoid any interruption to the breathing gas supply.

Say the dive supervisor selects 40 bar as the changeover pressure (a safety margin of around 20 – 25% of the available pressure is appropriate. Here we have (40-21) bar safety margin out of (100-21) bar available. This gives us 24% safety margin).

This means that the full available pressure is only 60 bar. This figure must be used in calculations of the time available on that quad.

For a 16 x 50-litre quad, which contains gas at 100 bar, with a safety margin of 40 bar, the calculation, is as follows:

Free gas volume (litres)	= water capacity (litres) x available pressure (bar)
	= 16 x 50 litres x (100 bar - 40 bar)
	= 48,000 litres
Time available	= gas available/gas consumption
	= 48,000 litres ÷ 35 litres/min
	= 1371 mins
	= 22.85 hours (22 hours 51 mins)

■ COMPRESSOR

When using a compressor for breathing gas supply, the compressor rate needs to be checked against the anticipated air requirements. There needs to be a safety margin applied and a bailout system employed.

WORKED EXAMPLE – COMPRESSOR SUPPLY PRESSURE

Worked example

A lightweight LP compressor delivers 250 l/min at a pressure of 15 bar. One diver is planning to work at 30msw. Her usual breathing rate is 35 l/min. Is the air supply sufficient?

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Solution

Absolute pressure	= Depth (msw)/10 + 1 bar
	= (30m ÷ 10) + 1 bar
	= 4 bar

Allow 10 bar for the demand valve.

Pressure required	= 4 bar + 10 bar
	= 14 bar

The compressor delivers 15 bar, so the pressure is suitable.

Gas consumption	= 4 bar x 35 l/min
	= 140 l/min

There is plenty of air available for one diver, as the compressor delivers 250 l/min.

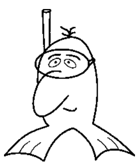
Now assume that you need two divers to complete the task. Is there enough air?

Two divers	= 2 x 140 l/min
	= 280 l/min

The compressor delivers only 250 l/min, so the air supply is inadequate for two divers.

CALCULATIONS RELATING TO BUOYANCY AND LIFTING

■ INTRODUCTION



Archimedes' Principle states:

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

Fresh water weighs 1kg per litre. Therefore, if an object of 1 litre volume is totally immersed, it will displace exactly one litre of water, and experience a buoyant force of one kg. If the object weighed 10kg in air, while immersed it will have an apparent weight of:

✔ 10kg – 1kg = 9 kg

An object will float when the buoyant force is greater than the mass (actual weight).

An object will sink when the buoyant force is less than the mass.

■ DIFFERENCES IN BUOYANCY BETWEEN SALT AND FRESH WATER

Fresh water has a density of 1.00 grams per cubic centimetre. One litre of fresh water will weigh one kilogram. Salt water has a density of 1.025 grams per cubic centimetre. One litre of salt water will weigh 1.025 kilograms.

The buoyant force in fresh water will be less than in salt water.

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WORKED EXAMPLE - BUOYANCY

Worked example

An object displaces a volume of five litres. What will the buoyant force be:-

- ✔ In fresh water?
- ✔ In salt water?

Solution

Fresh water: Buoyant force = volume displaced x density of liquid

- ✔ 5 litres x 1.000 = 5kg uplift

Salt water: Buoyant force = volume displaced x density of liquid

- ✔ 5 litres x 1.025 = 5.125kg uplift

Will an object with a mass of 145kg and a volume of 142 litres float or sink if immersed in salt water?

Mass = 145kg. Volume = 142 litres

- ✔ Buoyant force = volume x density of liquid. Or 142 litres x 1.025 = 145.55kg
- ✔ Apparent weight = 145kg – 145.55kg = - 0.55kg

As buoyant force is greater than the mass (145kg), the object will float.

Will the same object float or sink if immersed in fresh water?

- ✔ Buoyant force = volume x density of liquid. Or 142 litres x 1.00 = 142 kg
- ✔ Apparent weight = 145kg – 142kg = 3 kg

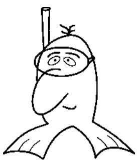
As buoyant force is less than the mass, the object will sink.

■ LIFTING

Lifting is a common task in occupational diving. Buoyancy calculations are often an important part of planning these tasks. For example, in recovery operations, you may need to perform calculations for how much air to use to lift an object to the surface using air bags. This will need to include the amount of air that needs to be released as the object ascends.

If the object is embedded in mud or silt on the seabed, calculating the lifting force required is more challenging. The suction forces created by the mud or silt are very difficult to estimate. It may be necessary to use air or water jets to remove some of the mud or silt prior to lifting.

When calculating the air used to lift the embedded object, it would be useful to calculate a maximum safe quantity of air to pump into the lifting bags. In other words, if too much air is pumped in, and the object suddenly releases, the buoyant force is so great that the object shoots to the surface in an uncontrolled ascent. By calculating a quantity of air that can be adequately released to avoid an uncontrolled ascent, you are ensuring that the situation remains under control and safe.



Remember: Never underestimate the impact of buoyant forces on an object during lifting operations.

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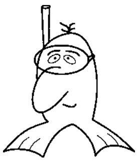
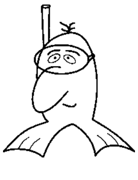
5 CHAPTER 5 – SUMMARY

PHYSICS AND PHYSIOLOGY



- ✔ Physics relates to the science of matter and energy and their interactions.
- ✔ Physiology relates to the functions and vital processes within the body.
- ✔ Physics and physiology are essential knowledge for a dive supervisor to conduct a dive operation safely.
- ✔ Gas equations (Boyle's Law, Charles' Law, Dalton's Law and Henry's Law) are used to calculate gas volumes, pressures, partial pressures and mass of gas absorbed.
- ✔ Risks due to the behaviour of gases in changing pressures are the risk of barotrauma, decompression illness and gas poisoning.
- ✔ Mixed gases are designed to improve safety and increase bottom time.
- ✔ Rebreathing systems recycle exhaled gases and extend the length of time an air supply will last.
- ✔ Thermal conductivity is greater in water, increasing the risk of hypothermia
- ✔ Visibility, colour and distance perception are affected by the behaviour of light underwater.
- ✔ Sound travels faster underwater, making it seem louder and making it difficult to locate the source.
- ✔ The safety implications of thermal conductivity, sound transmission, visibility, colour and distance perception need to be considered by the dive supervisor in the planning stage.
- ✔ When undertaking calculations, make sure all units are consistent or that conversions are carried out correctly.
- ✔ Breathing gas calculations are based on free gas volumes – the volume at the surface.
- ✔ Typical breathing rate for a working diver is 35 litres/minute.

BUOYANCY



- ✔ Buoyancy is calculated using Archimedes's principle, which states that any object wholly or partly immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.
- ✔ Lifting operations involving air bags use buoyancy principles and may need careful calculations.

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