PHYSICS FOR COMMERCIAL DIVERS

by

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Illustrations by Peter Holden

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Foreword

Anyone seriously involved with diving, professional or amateur, has dreamed of the *magnum opus*, the great diving reference book which would contain all the calculations and formulae that a diver would ever need to know.

Paul Williams, with his strange cocktail of life experiences as a qualified teacher, offshore Life Support Supervisor, diving school instructor and computer specialist, has all the qualifications for such a grand project.

With his unconventional approach, he has brought a fresh perspective to the subject of diving physics and presented it in a user friendly format. This book is the most original and useful that I have seen.

Georges Arnoux
Safety Manager
Stolt Comex Seaway Ltd

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Introduction

This book is intended mainly for commercial divers and life support crews working offshore. I hope it will also be of interest to sports divers and anyone interested in deep diving.

For this reason, I've included a few explanations that are not strictly necessary for commercial divers. I'll apologise in advance.

Where applicable, I've given units in the metric (MKS) system and the foot-pound (FPS) system. I haven't, however, gone to the trouble of reminding you every time that 1 bar and 1 AT are the same (for all practical purposes).

I occasionally mention safety limits, points of procedure and so on. Please remember that during diving operations, the only safety limits and procedures that you follow are the ones laid down in the company manual.

Formulae, units and logic

You don't have to read this if you don't want to. But if you miss it out, don't start moaning about the way I write out formulae (or formulas, if you prefer).

This is a widely used formula:

Free gas volume = floodable volume x pressure

Suppose that the floodable volume was 3.2 m^3 and the pressure was 150 bar. A lot of people write out the equation as:

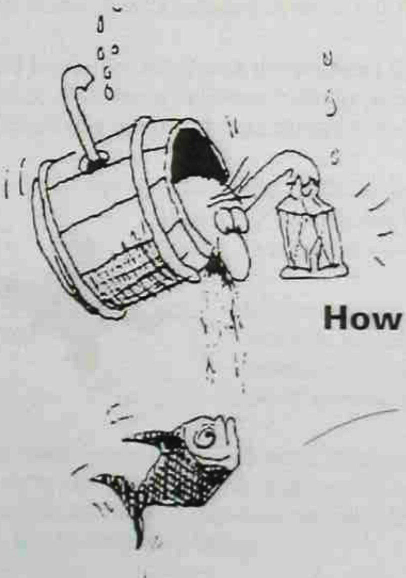
$$\text{Free gas volume} = 3.2\ \text{m}^3 \times 150\ \text{bar}$$

Those of you with a rigorous training in linguistic philosophy, Aristotlian logic and higher metaphysics will realise instantly that this is not the way to do it.

The final answer is in cubic metres, so what you should write is:

$$\text{Free gas volume} = 3.2 \times 150\ \text{m}^3$$

That's the way it's done in this book. The units at the end of an equation are the units of the final answer.



How long have you got?

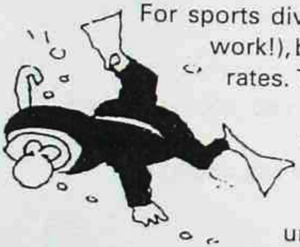
SECTION ONE

How much gas do you use?

A commercial diver is reckoned to use 35 litres (1.25 ft^3) of gas per minute. This is an average that can vary enormously from diver to diver, and with the work load. Gas recovery systems, where the diver's gas is recycled, are reckoned to have a loss of 5 litres (0.18 ft^3) per minute.

For emergencies, the Norwegian regulations reckon a breathing rate of 40 litres (1.5 ft^3) per minute. This is to take into account the effects of cold shock (if the diver's heating system has failed) and simple panic.

To the experienced sports diver, these figures sound high. But there's a world of difference between drifting gently along a coral reef at 10 msw and hauling a length of pipe through the mud at 100 msw.



For sports diving, stick to the figures you're using (if they work!), but for commercial diving use the recommended rates. That's what we'll use in this book.

35 litres is the **free gas volume** (FGV). This is the volume of gas at surface pressure, that's a pressure of 1 bar. All gas volumes are measured at surface pressure.

If the diver is working at 30 msw (99 fsw), the absolute pressure is 4 bar (if you're not familiar with gauge pressure and absolute pressure, see Appendix 2). The free gas volume going through his lungs is now 4 x 35 l/min, or 140 l/min (6 ft^3/min).

Gas consumption = Absolute pressure x 35 l/min

Gas consumption = Absolute pressure x 1.25 ft^3/min

$$\textbf{Absolute pressure} = \frac{\text{Depth(msw)}}{10} + 1\ \text{bar}$$

$$\textbf{Absolute pressure} = \frac{\text{Depth(fsw)}}{33} + 1\ \text{ATA}$$

Example 1

A diver is working at 120 msw for 4 hours. What volume of gas will he use?

$$\text{Absolute pressure} = \frac{\text{Depth(msw)}}{10} + 1 \text{ bar}$$

$$= \frac{120}{10} + 1 \text{ bar}$$

$$= 13 \text{ bar}$$

$$\text{Gas consumption} = \text{Absolute pressure} \times 35 \text{ l/min}$$
$$= 13 \times 35 \text{ l/min}$$
$$= 455 \text{ l/min}$$
$$= 0.455 \text{ m}^3\text{/min}$$

(Divide by 1000. Gas volumes are normally worked in cubic metres)

$$\text{In 4 hours, gas use} = 4 \times 60 \times 0.455 \text{ m}^3$$
$$= 109.2 \text{ m}^3$$

The diver will use 109.2 m^3 of gas

Example 2

A diver is working at 100 fsw for 30 minutes. What volume of gas will he use?

$$\text{Absolute pressure} = \frac{\text{Depth(fsw)}}{33} + 1 \text{ ATA}$$

$$= \frac{100}{33} + 1 \text{ ATA}$$

$$= 4.03 \text{ ATA}$$

$$\text{Gas consumption} = \text{Absolute pressure(ATA)} \times 1.25 \text{ ft}^3\text{/min}$$
$$= 4.03 \times 1.25 \text{ ft}^3\text{/min}$$
$$= 5.04 \text{ ft}^3\text{/min}$$

In 30 minutes, gas use $= 30 \times 5.04\ ft^3$
$= 151.12\ ft^3$

The diver will use 151.12 ft³ of gas

How much gas have you got?

In offshore work, gas is usually supplied in quads or superquads. A quad is normally a rack of 16 x 50 litre bottles, a superquad is normally a rack of 64 x 50 litre bottles. In this book, assume that's what the words mean, unless it states otherwise.

On the worksite, never assume anything. Go and look! A quad that only had 12 x 50 litre bottles could really mess up your dive plan.

Back to our 64 x 50 litre superquad:

Volume of the superquad = 64 x 50 litres
= 3200 litre
= 3.2 m^3.

This is known as the **floodable volume**, because that's the volume of water that you could pour in.

The volume of gas, the **free gas volume**, that the superquad can hold is considerably greater, because the gas is compressed.

Free gas volume = floodable volume x pressure

If the superquad contains gas at a pressure of 100 bar:

Free gas volume = floodable volume x pressure
= 3.2 x 100 m^3
= 320 m^3

The total volume of gas in the superquad is 320 m^3

Available gas

A typical scuba bottle holds about 2.5 m^3 or 90 ft^3 of gas when it's full.

This, of course, is the free gas volume.

The diver in Example 2 (at 100 fsw), uses 5.04 ft³/min. Using a scuba bottle, he could work for $\frac{90}{5.04}$ minutes or 17.8 minutes.

This simple calculation looks good on paper. But it assumes that he can use all the gas in the bottle (he can't), doesn't need any decompression time (he does), and doesn't have any reserve (silly).

In practical calculations, the total volume is not important. It's the **available** gas that matters, the volume that the diver can actually use.

You also have to base your calculations on a realistic dive plan, which includes getting down to working depth, getting back safely and having enough gas to cope with a crisis.

Here's a typical calculation, where the diver is using surface supplied equipment. To keep it simple, he's in saturation, so there are no decompression problems.

Suppose that the diver is working at 130 msw, breathing from a superquad at a pressure of 100 bar.

Although the pressure is 100 bar, the gas is being supplied to a diver at 130 msw, where the pressure is 14 bar. That's 14 bar he can't use.

It also takes a certain amount of pressure, say 10 bar, to drive the demand valve. That's another 10 bar he can't use.

So altogether, 24 bar are **not** available to supply the diver. The most that he can get out the superquad is 76 bar.

Safety margins

Most diving supervisors allow a considerable margin of error, and will change over to a new superquad when the pressure drops to 40 bar. In other words:

$$\text{Available pressure} = (100 - 40)\ \text{bar} = 60\ \text{bar.}$$

To find the available free gas volume, you need to know the floodable volume of the superquad:

$$\begin{aligned}\text{Volume of the superquad} &= 64 \times 50\ \text{litres}\\ &= 3200\ \text{litre}\\ &= 3.2\ \text{m}^3.\end{aligned}$$

$$\text{Free gas volume} = \text{floodable volume} \times \text{pressure}$$

In this case, the pressure is the available pressure.

$$\begin{aligned}\text{Free gas volume} &= 3.2 \times 60\ \text{m}^3\\ &= 192\ \text{m}^3\end{aligned}$$

This is the volume of gas that's actually available to the diver.

How long have you got?

If you know how much gas you have available and your gas consumption, a simple division will tell you how much time you've got.

$$\boxed{\textbf{Time available} = \frac{\textbf{Gas available}}{\textbf{gas consumption}}}$$

The diver is at 130 msw where the pressure is 14 bar (divide depth by 10 and add 1), so

$$\begin{aligned}\text{Gas consumption} &= \text{Absolute pressure} \times 35\ \text{l/min}\\ &= 14 \times 35\ \text{l/min}\\ &= 490\ \text{l/min}\\ &= 0.49\ \text{m}^3/\text{min}\end{aligned}$$

$$\text{Time available} = \frac{\text{Gas available}}{\text{gas consumption}}$$

$$= \frac{192}{0.49} \text{ minutes}$$

= 392 minutes
= 6 hours 32 minutes

The diver has enough gas available for 6 hours 32 minutes

(If you like to see how to do hours and minutes calculations on your calculator, look in Appendix 12)

So the diver can work for 6 hours 32 minutes. Even then, he's nowhere near the limits of his gas supply, and if anything should go wrong there's plenty of time to change over to a new quad.

In practice, of course, divers each do about four hours out of the bell during an eight hour bell run.

Example 3

A diver is working at 80 msw, breathing from a quad at a pressure of 150 bar. How long could he work for? (Assume that the quad will be changed over at 40 bar)

Floodable volume = 16 x 50 litres

(it's a quad, not a superquad!)

= 800 litres
= 0.8 m^3

Available pressure = (150 - 40) bar
= 110 bar

Free gas volume = floodable volume x available pressure
= 0.8 x 110 m^3
= 88 m^3

Gas consumption = Absolute pressure x 35 l/min

$$\text{Absolute pressure} = \frac{\text{Depth(msw)}}{10} + 1 \text{ bar}$$

$$= \frac{80}{10} + 1 \text{ bar}$$

$= 9$ bar

Gas consumption $= 9 \times 35$ l/min
$= 315$ l/min
$= 0.315\ m^3/min$

Time available $= \dfrac{\text{Gas available}}{\text{gas consumption}}$

Time available $= \dfrac{88}{0.315}$ minutes

$= 279$ minutes
$= 4$ hours 39 minutes   4HR 65

The diver has enough gas available for 4 hours 39 minutes

Other ways of working

Gas volumes are often given as free gas volumes when the container is full, like the volume of the scuba bottle at the start of this section. You have to work out the available gas in a slightly different way.

Free gas volume = Volume when full x $\dfrac{\textbf{available pressure}}{\textbf{pressure when full}}$

Example 4

A diver is working at 250 fsw. He's breathing from a quad which contains 22,500 ft³ of gas when it's at a pressure of 3000 psi. Just now, it's at 2750 psi. How long could the diver work for? (Assume that the quad will be changed over at 500 psi)

Available pressure $= (2750 - 500)$ psi
$= 2250$ psi

Free gas volume = *Volume when full x* $\dfrac{\text{available pressure}}{\text{pressure when full}}$

$= 22{,}500 \times \dfrac{2250}{3000}\ ft^3$

$$= 16875\ ft^3$$

$$\textit{Gas consumption} = \textit{Absolute pressure} \times 1.25\ ft^3/min$$

$$\textit{Absolute pressure} = \frac{Depth(fsw)}{33} + 1\ ATA$$

$$= \frac{250}{33} + 1\ ATA$$

$$= 8.58\ ATA$$

$$\textit{Gas consumption} = 8.58 \times 1.25\ ft^3/min$$
$$= 10.72\ ft^3/min$$

$$\textit{Time available} = \frac{\textit{Gas available}}{\textit{gas consumption}}$$

$$= \frac{16875}{10.72}\ minutes$$

$$= 1574\ minutes$$
$$= 26\ hours\ 14\ minutes$$

The diver has enough gas available for 26 hours 14 minutes

(That's a lot of gas. There's enough there for maybe three 8 hour bell runs, although gas would also be used to pressurise and flush the bell)

Surface supply compressors

So far, we've been talking about mixed gas divers at spectacular depths. An air diver (whose life is often a lot harder) is generally supplied from an LP compressor.

Compressors are rated according to the volume of air that they take in each minute. That's the free gas volume of the air that is supplied to the diver.

The volume of air used by the diver will vary according his work rate, and the variations are dealt with by the reservoir on the compressor.

Supply pressure

The supply pressure must, of course, be enough to get the air to the diver. At 50 msw (165 fsw), which is generally accepted as the maximum depth for air diving, the pressure is 6 bar. Allow 10 bar for the regulator, and the supply pressure must be at least 16 bar. Say 20 bar for safety. On the foot pound system, gas pressures are normally given in psi, so that would be about 300 psi.

Most commercial compressors supply air at pressures well above this. Lightweight compressors may not. Always check!

If the supply pressure is OK, you just need to check the volume.

Example 5

An LP compressor supplies 30 ft³/min at 300 psi. The diver plans to work at 100 fsw. Is the air supply sufficient?

First, check the pressure:

$$\text{Absolute pressure} = \frac{\text{Depth(fsw)}}{33} + 1 \ \text{ATA}$$

$$= \frac{100}{33} + 1 \ \text{ATA}$$

$$= 4.03 \ \text{ATA}$$

Allow 10 ATA for the demand valve

$$\begin{aligned}\text{Pressure required} &= (4.03 + 10)\ \text{ATA}\\ &= 14.03\ \text{ATA}\\ &= 14.03 \times 14.7\ \text{psi}\\ &= 206\ \text{psi}\end{aligned}$$

(There are 14.7 psi in 1 ATA. See Appendix 3)

The compressor delivers 300 psi, so the pressure is OK

$$\text{Gas consumption} = \text{Absolute pressure} \times 1.25\ \text{ft}^3/\text{min}$$

$$\text{Absolute pressure} = 4.03\ \text{ATA}$$

$$\begin{aligned}\text{Gas consumption} &= 4.03 \times 1.25\ \text{ft}^3/\text{min} \\ &= 5.04\ \text{ft}^3/\text{min}\end{aligned}$$

The compressor delivers 30 ft^3/min, so the volume is OK

Example 6

A lightweight LP compressor delivers 250 l/min at a pressure of 15 bar. Two divers are planning to work at 30 msw. Is the air supply sufficient?

First, check the pressure:

$$\begin{aligned}\text{Absolute pressure} &= \frac{\text{Depth(msw)}}{10} + 1\ \text{bar} \\ &= \frac{30}{10} + 1\ \text{bar} \\ &= 4\ \text{bar}\end{aligned}$$

Allow 10 bar for the demand valve

$$\begin{aligned}\text{Pressure required} &= (4 + 10)\ \text{bar} \\ &= 14\ \text{bar}\end{aligned}$$

The compressor delivers 15 bar, so the pressure is OK

$$\text{Gas consumption} = \text{Absolute pressure(bar)} \times 35\ \text{l/min}$$

$$\text{Absolute pressure} = 4\ \text{bar}$$

$$\begin{aligned}\text{Gas consumption} &= 4 \times 35 \times 2\ \text{l/min (there are 2 divers)} \\ &= 280\ \text{l/min}\end{aligned}$$

The compressor only delivers 250 l/min, so the volume is insufficient.

Gas use in a an emergency

A surface supplied diver always carries a scuba bottle as a back up. This is known as a bail out bottle. The deeper you are, of course, the less time it gives you in an emergency.

Example 7

A typical bail out bottle has a floodable volume of 12 litres. (This is a 100 ft^3 scuba bottle). How much time has a diver got if his surface supply fails at 200 msw (660 fsw)?

The bail out bottle is at a pressure of 180 bar. At 200 msw, the pressure is 21 bar, add on 10 bar for the regulator, and that's 31 bar he can't use.

$$\text{Available pressure} = (180 - 31)\ \text{bar} = 149\ \text{bar}$$

$$\text{Free gas volume} = \text{floodable volume} \times \text{available pressure} = (12 \times 149)\ \text{litres} = 1788\ \text{litres.}$$

Sounds plenty. But this is an emergency, so he's going through 40 l/min and he's at 21 bar.

$$\text{Gas consumption} = (40 \times 21)\ \text{l/min} = 840\ \text{l/min.}$$

$$\text{Time available} = \frac{\text{Gas available}}{\text{gas consumption}}$$

$$= \frac{1788}{840}\ \text{minutes}$$

$$= 2.12\ \text{minutes}$$

In other words, he's only got about 2 minutes.

It's amazing how fast a diver can get back to the bell, but it only takes a snagged umbilical to turn a crisis into a disaster.

What about the temperature?

The diver swimming for his life at 200 msw only had 180 bar in his bail out bottle. He could have had it pressurised to 200 bar, or even 210 bar. Not much of an increase, but important when every second counts.

He probably did fill it to 200 bar, but he forgot about the temperature. The pressure varies directly with the temperature, the hotter it is, the higher the pressure.

Gas heats up when it's compressed into a bottle or quad. Suppose the temperature rises to 30°C during filling. If the diver goes out into the cold North Sea, the temperature will drop to about 4°C. And the pressure will drop accordingly.

$$\textbf{Final pressure} = \textbf{Initial Pressure} \times \frac{\textbf{Final temperature (°K)}}{\textbf{initial temperature(°K)}}$$

In the formula, temperatures are in °K or degrees Kelvin. To convert to °K just add 273 to the temperature in °C. This gives you the temperature measured from absolute zero. Look in Appendix 4 if you'd like to know more.

When the bottle is filled to 200 bar it's at a temperature of 30°C or 303°K. The temperature drops to 4°C or 277°K

$$\text{Final pressure} = \text{Initial Pressure} \times \frac{\text{Final temperature (°K)}}{\text{initial temperature(°K)}}$$

$$= 200 \times \frac{277}{303} \text{ bar}$$

$$= 183 \text{ bar}$$

The temperature drop has caused a pressure drop of 17 bar. That means 17 bar less in an emergency.

Don't worry too much about working out this type of calculation. Unless you carry a thermometer around with you, you won't have enough information to do it in practice. Just remember the consequences.

Temperature calculations can be useful when you're dealing with chambers. Have a look in Section 4.