Decompression Theory

An Explanation of Professor A.A. Buehlmann's ZH-L16 Algorithm

by Paul Chapman

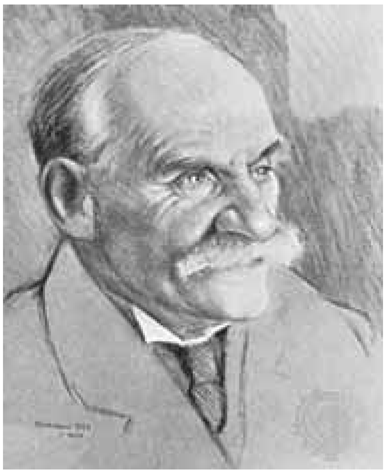
The following is a summary of the decompression algorithm described by Dr A.A. Buehlmann in the fourth edition of his book **Tauchmedizin** (diving medicine) published in 1995 (only in German.) The book contains a considerable amount of other information and is published by Springer-Verlag ISBN 3-540-58970-8. Rumor has it that at the time of writing (November 1999) an English translation is being prepared for publishing, so hopefully, in due course, this document will become redundant.

Note to new divers and potential new divers:

This information is presented for general interest. Don't be scared off by what you see here - you don't need to learn any of this to become a safe and competent scuba diver. You will however need to understand dive planning.

The algorithm is simply a "recipe" for modeling the behavior of inert gases, which diffuse in and out of our body tissues when breathed under varying pressures. The intention is that if the recipe models the actual processes in our bodies accurately enough, it can be used to plan dives (and other pressure exposures) with a view to avoiding decompression sickness.

It is important to realize that the model is entirely arbitrary in the sense that it in no way represents the actual physical processes which are taking place, it simply attempt to model the real-life results mathematically. This article is intended mainly as a description of the algorithm, not as a complete description of decompression physiology and therefore mentions only physiology principles relevant to the algorithm.



Background

Scottish scientist **John Scott Haldane** (1860-1936) is generally considered the founding father of modern decompression theory. In the last century (1896-1907) Haldane experimented on goats in an attempt to find a solution to the problem of **caisson disease**, experienced by men working in pressurized bridge and tunnel construction areas. Research suggested that gases breathed under pressure by the workers were diffusing into the body's tissues, and that when these gases came out in the form of bubbles in the body, the workers got caisson disease, or what we now call decompression sickness, or **the bends**.

Haldane's work led him to consider the body as a group of tissues in parallel. This meant the tissues were all exposed simultaneously to the breathing gases at ambient pressure, but able to react to them in their own individual ways. No gas transfer from one tissue to another was considered. This principle is still in use and is the basis of many, but not all, current decompression models. The model used in the production of the British Sub Aqua Club BSAC-88 dive tables, for example, used a single block of **tissue** along which gas diffused, while the Canadian DCIEM model uses a range of tissues, but arranged in series - only the first of a range of tissues is exposed to the ambient pressure and gas diffusion takes place from one tissue to the next.

Haldane also noticed that the body could tolerate a certain amount of excess gas with no apparent ill effects. Caisson workers pressurized at two atmospheres (33 feet) experienced no problems, no matter how long they worked. These two ideas, gas traveling though the body tissues and the theory of a **tolerable overpressure** formed the basis of Haldane's work. The tricky bit was to model exactly how the gas moved through the body and exactly what amount of overpressure was acceptable and Haldane actually achieved this with considerable success.

Others developed Haldane's ideas over the years. In the mid-1960's US Navy Medical Corps Captain Robert Workman refined the idea of allowable overpressure in tissues, discounting oxygen and considering only inert gases in the breathing mix, such as nitrogen and helium. Workman's maximum allowable overpressure values (what he called **M-values**) were more complex than Haldane's, varying with depth and with tissue type.

At around the same time Professor Albert Buehlmann was working on similar research at the University Hospital in Zurich. Buehlmann's research spanned over 30 years and was published as a book, **Dekompression - Dekompressionskrankheit** in 1983. This book, published in English in 1984, made fairly comprehensive instructions on how to calculate decompression available to a wide audience for the first time and therefore Buehlmann's work became the basis for many dive tables, computers and desktop decompression programs. Three other editions were published, the last in 1995, on which this document is based.

Basic Ideas

Due to differences in **perfusion** (blood flow) and **diffusion** (rate of gas flow from one place to another) and other factors, the inert gases we breathe are dissolved into our different body tissues at different speeds. Tissues with high rates of diffusion, which have a good blood supply, build up a gas load more quickly. The blood itself, major organs, and central nervous system fall under this heading and we call them **fast** tissues. Other tissues build up a gas load more slowly. Progressively slower tissues include muscle, skin, fat and bone.

Many tissues, through good blood supply, are exposed almost immediately to higher inert gas pressures, while others have to wait for gas to reach them by diffusion from other surrounding tissues. In this sense the body tissues are both serial and parallel. Although a fast tissue will build up a higher inert gas load or **on-gas** more quickly when the pressure increases, it will also be able to get rid of that gas load more quickly than a slower tissue when the pressure drops, a process we call **off-gassing**. It

is assumed that tissues on-gas and off-gas according to the theory of **half-times**.

Many natural phenomena are described this way, including radioactive decay. The idea is that when a tissue is exposed to a higher inert gas pressure, gas will flow into that tissue. After the **half-time** the pressure of gas in the tissue will be half way to equaling the pressure of the gas outside. After a second half-time, the gas pressure in the tissue will have risen by half of the remaining difference (i.e. by a further quarter,) making it 75%, or three-quarters, of the way to equaling the external gas pressure. After a third half-time, the rise is 12.5% (87.5% total) and so on. By this method the pressure in the tissue never quite reaches the same level as the surrounding gas, but after 6 half-times (equal to 98.4%,) it is close enough and we say the tissue is **saturated**.

At this point gas will diffuse into the tissue at the same rate that it diffuses out and the tissue experiences no further overall change in gas load. If the pressure then increases (the diver goes deeper,) the tissue will begin to on-gas again. If the pressure reduces, the tissue will off-gas, again following the half-time principle. After six half-times, the tissue will again be **equilibrated** with its surroundings. As well as differing for each tissue, half-times will vary for different gases, since they diffuse at different rates. For real human tissues the nitrogen half-times will vary from a few seconds (blood) to many hours. For helium, half-times are thought to be about 2.65 times faster than nitrogen, since helium diffuses more quickly.

If pressure is reduced by too much on a tissue, the gas will be unable to follow the diffusion route, via the bloodstream, back to the lungs and will form bubbles in the actual tissue, leading to many of the symptoms that we know as decompression sickness. So how much pressure reduction is too much? It has been shown by experimentation that faster tissues like blood can tolerate a greater drop in pressure than slower tissues, without bubble formation. One of the challenges to Buehlmann in formulating his algorithm was to quantify this difference in a mathematical formula that could be used to help calculate decompression profiles. We'll look at his solution in a moment.

The Algorithm

For his **ZH-L16** algorithm Buehlmann chose to split the body into **16 tissues** and give them a range of half-times, from several minutes to several hours. It is important to remember that these tissues do not represent any specific real tissues in the body and the half-times are simply chosen to give a representative spread of likely values. They do not represent actual tissues, or the actual half-times for any particular tissue. For this reason the often-used description of the 16 sections as **tissues** is confusing and they will be referred to in future as **compartments**. Buehlmann named his algorithm from Zurich (ZH), limits (L) and the number of M-value sets (16).

When exposed to pressure, each compartment on-gasses according to its given half time, so at any point we can calculate how much inert gas pressure exists in each compartment. There is a standard mathematical form for half-time calculation, Buehlmann made some additions to it to make a complete before/after formula for the inert gas pressure in any given compartment after any given exposure time. Here is the formula as published in **Tauchmedizin**, the names of the constants have been changed to make them more understandable in English, but the formula is the same:

$$\text{Pcomp} = \text{Pbegin} + [\ \text{Pgas} - \text{Pbegin}\ ] \times [\ 1 - 2 \wedge (\ - \text{te} / \text{tht}\ )\ ]$$

where:

Pbegin	= Inert gas pressure in the compartment before the exposure time (ATM)
Pcomp	= Inert gas pressure in the compartment after the exposure time (ATM)
Pgas	= Inert gas pressure in the mixture being breathed (ATM)
te	= Length of the exposure time (minutes)
tht	= Half time of the compartment (minutes)

and ^ stands for exponentiation

1 ATM = 14.7 psia (1 Atmosphere, or sea level standard pressure)

Example:

A diver descends from the surface to 100 feet on air and waits there ten minutes. The partial pressure of nitrogen in the breathing gas **Pgas** is 4 x 0.79 = 3.16 ATM. Let's pick a compartment, say number five. The nitrogen half-time for compartment five **tht** is 27 minutes. The nitrogen partial pressure in compartment five on the surface **Pbegin** is 0.79 ATM, assuming the diver hasn't already been diving or subject to any altitude changes. The length of the exposure **te** is ten minutes. Plugging these values into the equation, we get:

$$\textbf{Pcomp} = 0.79 + [\ 3.16 - 0.79\ ] \times [\ 1 - 2 \wedge (\ - 10 / 27\ )\ ]$$
$$= 1.33 \text{ ATM}$$

So the partial pressure of nitrogen in compartment five of our diver would be 1.33 ATM. In reality, the diver couldn't have made an instantaneous descent to 100 feet and would have been taking on gas during the descent as well. We could average the pressure during the descent and repeat the above calculation to get an idea of the extra gas, or simply repeat the calculation many times at short intervals during the descent. A computer makes this easy.

You can repeat this calculation, of course, for all the other compartments, you just need to know the half-times, (See Table 1) Again, a computer is the ideal tool for this job. The beauty of the equation is its versatility. Absolute pressure (not depth) is used everywhere, as is the actual partial pressure of the inert gas being breathed, so we can ascend or descend to/from any pressure, breathe any gas, change gases, go flying after diving, stay on the surface, do a repetitive dive or anything we can think of.

Now we know the inert gas pressure in any given compartment at any time, we need to know the depth (or actually the pressure) that we can ascend to safely. We already mentioned that this would vary for each compartment, with faster compartments tolerating a greater pressure drop than slower ones. Buehlmann decided that the amount of pressure drop that a certain compartment could tolerate without bubble formation could be mathematically linked to its half-time. He first derived two factors, which he called "**a**" and "**b**" from the half-time (so each compartment has its own pair of a and b values), then he used these factors to calculate the pressure that we could ascend to. The **a** and **b** modifiers are obtained from the following formulas:

a = 2 x (tht ^ -1/3)

b = 1.005 - (tht ^ -1/2)

where **tht** is the half-time for the compartment.

For example, the half-time for compartment 5 is 27 minutes, so

a	= 2 x (27 ^ -1/3) = 0.6667
b	= 1.005 - (27^ -1/2) = 0.8125

Remember that the half-times vary for different gases, so each gas will have its own set of half-times, **a** and **b** values. (see Table 1)

Now that we know **a** and **b**, we can use a formula to calculate the pressure that we can ascend to for each compartment. Here is the formula Buehlmann chose to use:

Pambtol = (Pcomp - a) x b

where:

Pcomp = the inert gas pressure in the compartment (ATM)
Pambtol = is the pressure you could drop to (ATM)

and **a** and **b** are the **a** and **b** values for that compartment and the gas in question (See Table 1)

Continuing the example above, we found that a exposure for ten minutes to 4 ATM pressure (100 feet depth), led to a nitrogen pressure of 1.33 ATM in compartment 5. The **a** and **b** values for compartment 5 were 0.6667 and 0.8125 respectively. Plugging these into the above gives:

Pambtol	= (1.33 - 0.6667) x 0.8125
	= 0.54 ATM

Pressure at sea level is taken to be 1 ATM and the above equation shows us that we can actually ascend to a pressure lower than that (i.e. above the surface.) In other words, according to the model, after 10 minutes at 100 feet (4 ATM) we could ascend straight to the surface with no bubble formation in compartment 5 assuming we were breathing air. This is a "no-stop" dive, as we'd expect from looking at our dive tables !

If we tried our 100 foot exposure for 50 minutes, we would find the nitrogen partial pressure in compartment five was 2.5 ATM (from the first equation) and our pressure could drop to 1.49 ATM. This pressure is just under 16 feet depth, so this is the maximum depth that compartment 5 would allow us to ascend to after 50 minutes at 100 feet.

Using the same depth and 50 minutes, if we repeat this method for all the other compartments, we'll find different values, for example:

Compartment 3: Half-time = 12.5 minutes

a	= 0.8618
b	= 0.7222
Pcomp	= 3.01 ATM
Pambtol	= (3.01 - 0.8618) x 0.7222
	= 1.55 ATM (or approximately 20 feet depth)

Compartment 10: Half-time = 146 minutes

a	= 0.3798
b	= 0.9222
Pcomp	= 1.29 ATM

Pambtol	= (1.29 - 0.3798) x 0.9222
	= 0.84 ATM (still above the surface)

Once we've repeated this for each compartment, we cannot ascend any shallower than the deepest of the tolerated depths. In our three-compartment example, this is 20 feet. This is called our **decompression ceiling** and the compartment concerned (compartment 3) is said to "control" the decompression at this point. In general, faster compartments will control short, shallow dives. Long shallow dives and short, deep dives will see a shift towards the middle compartments as controllers while long, deep dives will be controlled by the slower compartments.

The controlling compartment will often shift during a decompression. For example, a short deep exposure may see the initial ceiling limited by the faster compartments, but as these off-gas quickly the control shifts to the slower, mid-range, compartments. As you can imagine, calculating the gas loads for a sequence of several dives of differing depths and durations is quite involved. Although the math is actually straightforward, as we've seen, the number of calculations and constant shifting of the controlling compartment and its associated decompression ceiling make it a great job for a computer.

If we were actually planning a decompression for our 100 foot, 50 minute dive, we could ascend right up to the 20 foot ceiling, but it is more usual to choose a convenient interval for decompression stops, say every 10 feet, then you'd ascend to the nearest multiple of 10 feet that is below the decompression ceiling. In this example that is 20 feet. At this point the inert gas pressure in the more highly loaded compartments will be above the inert gas pressure in the breathing mix and those compartments will start to off-gas. Other compartments may have inert gas pressures lower than the breathing gas and these compartments will still be on-gassing.

We start the half-time calculations again. The formula is identical taking reductions in pressure (ascents) into account automatically. During the ascent the inert gas partial pressure being breathed **Pgas** drops, whereas the pressure in the compartment **Pbegin** hasn't caught up yet, so the **[Pgas - Pbegin]** part of the equation becomes negative. Don't forget the driving force for the gas diffusion (in this model, at least) is the difference between the inert gas pressure in the compartment and the ambient partial pressure of the inert gas.

At 20 feet the PPN2 (partial pressure of Nitrogen) in air is 1.26 ATM. In our example, the nitrogen pressure in compartments 3 and 5 was 3.01 ATM and 1.33 ATM respectively. These are both higher than the 1.26 ATM ambient PPN2, so compartments 3 and 5 will off-gas at this decompression stop. The PPN2 in compartment 10 however has only reached 0.29 ATM. This compartment will continue to on-gas at 20 feet depth, although at a slower rate than before because the ambient PPN2 is lower than at 100 feet.

The ceiling will gradually get shallower as the compartments off-gas, eventually reaching our chosen next stop depth of 10 feet. At this point we ascend to this depth and start the process again, until we reach a point where the ambient pressure **Pambtol** for all compartments is less than, or equal to, one and we can reach the surface.

That's all there is to it. Calculations can continue while you're on the surface (compartments continue to off-gas), so we can allow for a surface interval between dives and when we go down for our next dive some compartments may still be partially loaded. This loading will automatically be added to any additional gas gained during the dive, adjusting the decompression accordingly.

Flying or ascending to altitude is just a matter of ascending through the atmosphere. The calculations are the same, it is just that the pressure changes may take thousands of feet of air as opposed to just a few feet of water. If we know the cabin pressure in an airliner (say 8000 feet) we can use this as our ceiling and carry on calculating until we can reach it ... this is our "time to fly".

The formulas use inert gas partial pressure throughout, so diving with Nitrox is automatically accommodated. Likewise Trimix (oxygen, nitrogen and helium mixes) and alternative decompression gases (usually with lower proportions of inert gas) can all be accommodated within the same basic algorithm as long as we know the half times and the a and b values for the gases. Where multiple inert gases are used, an intermediate set of a and b values are calculated based on the gas proportions.

Table 1

ZH-L16A Half-times, "a" and "b" values for Nitrogen and Helium

Compartment	**Nitrogen**			**Helium**		
	Half-time	**a Value**	**b Value**	**Half-time**	**a Value**	**b Value**
1	4.0	1.2599	0.5050	1.5	1.7435	0.1911
2	8.0	1.0000	0.6514	3.0	1.3838	0.4295
3	12.5	0.8618	0.7222	4.7	1.1925	0.5446
4	18.5	0.7562	0.7725	7.0	1.0465	0.6265
5	27.0	0.6667	0.8125	10.2	0.9226	0.6917
6	38.3	0.5933	0.8434	14.5	0.8211	0.7420
7	54.3	0.5282	0.8693	20.5	0.7309	0.7841
8	77.0	0.4701	0.8910	29.1	0.6506	0.8195
9	109.0	0.4187	0.9092	41.1	0.5794	0.8491
10	146.0	0.3798	0.9222	55.1	0.5256	0.8703
11	187.0	0.3497	0.9319	70.6	0.4840	0.8860
12	239.0	0.3223	0.9403	90.2	0.4460	0.8997
13	305.0	0.2971	0.9477	115.1	0.4112	0.9118

14	390.0	0.2737	0.9544	147.2	0.3788	0.9226
15	498.0	0.2523	0.9602	187.9	0.3492	0.9321
16	635.0	0.2327	0.9653	239.6	0.3220	0.9404

Modifications for the Real World

Take note that all the above is to be read in the context of referring to the **ZH-L16** model, not to our own bodies. Buehlmann carried out a considerable amount of actual testing to validate the **ZH-L16** algorithm, but only using nitrogen as the inert gas. The half times for helium were derived from those for nitrogen, based on the speculative idea that the relative diffusivity of the gases was all that mattered. Since the a and b values are further derived from the half times, these also fall under the heading of **educated guesswork**.

Sadly, Buehlmann died before he was able to put his theoretical figures for helium to any extensive tests. It appears that Buehlmann's values for helium may be rather too conservative, and for years the result has been that people have assumed that decompressions from helium would be longer than from nitrogen, simply because that was what the formula told us. In fact helium is generally a much more "deco-friendly" gas than nitrogen, being less soluble in our tissues. The rapidly diffusing gas is more prone to bubble formation, requiring control of ascent rates and decompression stops that start deeper than nitrogen. The payback is shorter shallow stops and a reduced overall time for decompression.

A huge number of factors affect inert gas absorption, elimination and our susceptibility to decompression sickness. Some of these factors we know, some we guess at and some, no doubt, remain to be discovered. Among the first two categories are:

- Repetitive, yo-yo, reverse and bounce dive profiles
- Rapid ascents
- Missed decompression stops
- Heavy workloads
- Exercise, or lack of, during decompression
- Cold
- Flying after diving
- Poor physical conditioning
- Inter-pulmonary shunts
- Drug use (including alcohol)
- Dehydration
- Age

In an attempt to address some of these factors, Buehlmann suggested and made several modifications to his algorithms. For dive table production, the "**a**" values were altered to be a little more conservative, principally in the middle compartments, resulting in a variation of the algorithm called **ZH-L16B**. Further variations to both middle and upper "**a**" values are used in **ZH-L16C**, intended for use in dive computers, where the exact depth and time tracking removed some of the natural conservatism associated with table use. Attempts to include the effects of some of the other predisposing factors mentioned above led to the **ZH-L8 ADT** "adaptive" algorithm, implemented on the latest Aladdin dive computers.

Dive computers and planning programs for personal computers, typically implement these modifications and/or variations of their own in an attempt to make the dive profiles they generate more realistic, or more usually, just "more conservative". Modifications include:

- planning dives deep and/or longer than actual
- further tweaking of the **a** and **b** values
- limiting compartment over-pressure **Pambtol** to a percentage of the calculated value
- changing the amount of inert gases by some factor
- using longer half-times for the off-gassing phase of the profile
- adding more compartments
- and any number of other factors and combinations of factors.

It is interesting to note that the model clearly tells us that there is no such thing as a "no-decompression" dive. We begin to on-gas immediately we descend. What we call a no-decompression dive is really one where the ceiling is still above the surface. As the dive goes on and the ceiling reaches the surface, we can factor in the ascent rate and gain a few more minutes "no-decompression time".

Modern Ideas

The reality is that we will never get truly accurate decompression tables or computers. The chaotic nature of our own physiology means a certain amount of conservatism will be required. The best we can generally hope for are ones that work most of the time, for most people. It is highly likely that current tables are much too conservative for some individuals, while being overly liberal for others. As our knowledge of decompression physiology improves, this holds out the hope of tables, or more likely computer programs, tailored to some extent for the individual. Organizations such as the Woodville Karst Plain Project, with a large database of extreme dive exposures, and knowledgeable and committed team members, have achieved great advances in this area.

From Doppler studies, we now know that bubbles form in divers after most dives. Although causing no noticeable symptoms, gas elimination from these so-called **silent bubbles** occurs differently from gas dissolved in the blood. A reduction in ambient pressure will cause these bubbles to grow regardless of inert gas diffusion. Buehlmann's algorithm assumes all gas is being eliminated in the dissolved phase (i.e. dissolved in the tissues) and does not take these factors into account. Bubble mechanics formulae such as Bruce Weinke's Reduced Gradient Bubble Model attempt to model gas elimination in the gas-phase (bubbles) as well as dissolved gas.

Finally, helium is becoming accepted as a more deco-friendly gas than nitrogen. As well as the benefits of narcosis reduction, further experimentation holds out the possibility of faster decompressions than were previously thought possible and will probably include the use of helium in decompression gases as well as bottom mixes. Helium is expensive, which has limited its use in sport diving, however rebreathers may eventually become reliable and simple enough for the average scuba diver to take advantage of helium mixtures economically and safely.

Further Reading

The Encyclopedia of Recreational Diving
PADI - ISBN 1-878663-02-X

As an introduction to recreational diving, it's hard to beat PADI's encyclopedia. Chemistry, physics, physiology, equipment and the aquatic environment are explained simply and clearly. Offers a great deal more than the information contained in an open water diving course without getting too technical in its language. Recently reprinted with more up-to-date information.

Diving Physiology in Plain English
Jolie Bookspan - Published by UHMS Inc - ISBN 0-930406-13-3

The natural next-step from the "The Encyclopedia of Recreational Diving" (above), Dr Bookspan takes us to the next level and explodes a few commonly held misconceptions along the way. Some medical terms are used, but they're explained as we go along and topics such as decompression tables, immersion effects, gender issues, diving injuries, exercise and nutrition are introduced in a chatty and easy to read manner.

Pocket Medical Dictionary
Edited by Nancy Roper - Published by Churchill Livingstone - ISBN 0-443-03180-0

Several of the following books are written with the assumption that the reader is au fait with medical terminology. In fact this is not such a handicap for the lay reader as you may assume. For the most part the terminology is a combination of prefixes, such as "hypo" (say "high po" = under or below), a root word, such as "glyc" (say "glike" = sugar) and suffixes, such as "ia" (say "eee aah" = a condition or process). Thus the medical term "hypoglycemia", becomes the simple "too little (blood) sugar"...easy! As you can imagine, a grasp of the meaning of a few prefixes, roots and suffixes can have you sounding like an extra from ER in no time. The Pocket Medical Dictionary, published in association with the Royal Society of Medicine, fills in the blanks in double-quick time, while "Physiology & Anatomy" (below) adds flesh to the bones.

Physiology & Anatomy
John Clancy & Andrew J. McVicar - Published by Edward Arnold - ISBN 0-340-63190-2

This is an incredibly interesting book for the non-medical reader. Sub-titled "a homeostatic approach" it not only explains how the systems of the body work, but how they inter-react to maintain the balance ("homeostasis") that we need to sustain life and what happens when that balance is upset. Illustrated in color throughout, it's a must.

Resuscitation Handbook
Peter J.F. Baskett - Published by Times Mirror International Publishers Ltd - ISBN 1-56375-620-X

Advanced life support techniques for those already familiar and well practiced in basic life support. The theory presented is valuable but the practical skills can only be developed in conjunction with a properly run advanced life support course.

The Physiology and Medicine of Diving
Peter Bennett & David Elliott - Published by W B Saunders - ISBN 0-7020-1589-X

Generally known as "Bennett & Elliott" this is the diving medical bible. In fact both Bennett and Elliott are prolific contributors to many other publications, including "Bove & Davis" (below), but this is probably the most comprehensive text on the subject available. It's uncompromisingly directed at the medically-educated reader, but don't let that put you off. Get your copies of the "Pocket Medical Dictionary" and "Physiology & Anatomy" alongside, with a pencil to make notes in the margin and you'll surprise yourself in no time.

Bove and Davis' Diving Medicine
Edited by Alfred A Bove - Published by W B Saunders - ISBN 0-7216-6056-8

Slimmer and less well known than the previous and following texts (around 400 pages as opposed to 600 and 550 respectively), Bove & Davis nevertheless fields heavyweight contributions from many of the professions big guns. In common with Bennett & Elliott, B&D's chapters conclude with an extensive reference section which could provide a lifetime's research in their own right. If you don't have a medical degree, keep a copy of the "Pocket Medical Dictionary" to hand.

Diving and Subaquatic Medicine
Edmonds, Lowry & Pennefather - Published by Butterworth Heinmann - ISBN - 0-7506-2131-1

A personal favorite, "ELP" offers in-depth information with a slightly less clinical approach. Some less-commonly published data is included (have you had "scuba diver's thigh"?) and each chapter concludes with a useful "recommended reading" section.

Tauchmedizin
A.A. Buehlmann - Published by Springer-Verlag - ISBN 3-540-58970-4

"Tauchen" is the German verb "to Dive" and you can guess the rest of the title.

My thanks to the members of the Woodville Karst Plain Project for providing both valuable information and the inspiration to learn more and do it right. If you have any comments on this document, the author would be pleased to hear from you. **Paul Chapman** may be contacted at paul@delsys.demon.co.uk or at **Professional Diver Training** on 0151 343 1601.

This excellent article has been reformatted for the web from the original document by Paul Chapman, and "Americanised" with units, spellings, and grammar, but is otherwise unchanged. I could not have written a better description of this subject.

The inverse-exponential basis of Buehlmann's algorithm is the natural mathematical model for gas diffusion. Decompression involves many factors that are too complex and uncertain to model. Rather than using calculations of ever-increasing complexity and doubtful accuracy and realism, Buehlmann runs 16 simple simulations in parallel, and selects the worst case. This is a very broad-based approach to modeling something that is inherently unpredictable.

Occam's Razor is a logical principle attributed to the medieval philosopher William of Occam (or Ockham). The principle states that one should not make more assumptions than the minimum needed. In other words, the simplest solution to a problem is usually the right one.

-- Editor, NJSD

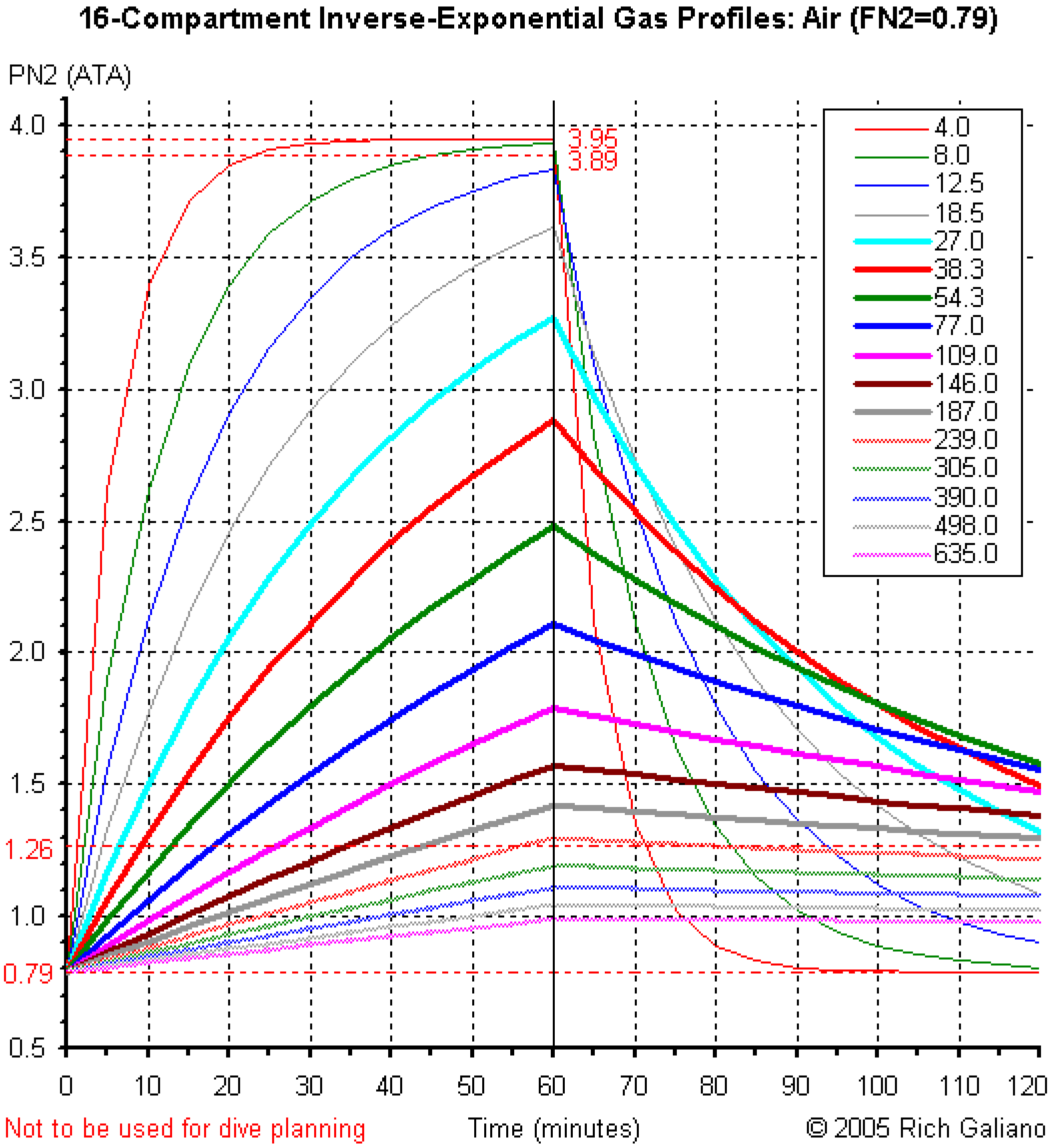
- Introductory "Lessons" About Dissolved Gas Decompression Modeling - Erik Baker
- Calculating the No-Stop Time by Erik Baker
- Understanding M-values by Erik Baker
- Clearing Up The Confusion About "Deep Stops" by Erik Baker
- Oxygen Toxicity Calculations by Erik Baker

- DIY Decompression by Stuart Morrison
- The Variable Permeability Model by Dan Reinders & Richard Pyle
- Abyss / Reduced Gradient Bubble Model by Bruce Weinke

more

Decompression Theory 2

You can make neat colorful graphs of nitrogen loading curves, so here we go ...



Theoretical nitrogen pressure curves for 16 Buehlmann compartments.

- At time = 0, ambient pressure is instantaneously increased from 1 ATA to 5 ATA.
(or 130ft, PN2 = 3.95 ATA)

- At time = 60, ambient pressure is instantaneously reduced back to 1 ATA (surface)

- This is obviously not possible in real life, but is suitable for purposes of exposition.
If this was a real dive profile, it would kill you in more ways than one !

From the gas loading curves, it is apparent that the four "fastest" compartments (4.0 - 18.5, thin lines) become largely or completely saturated, and that they also unload very quickly, such that after one hour of off-gassing, they are all back within the "safe" pressure ratio of 1.6:1 (equal to 1.26:0.79 at the surface.)

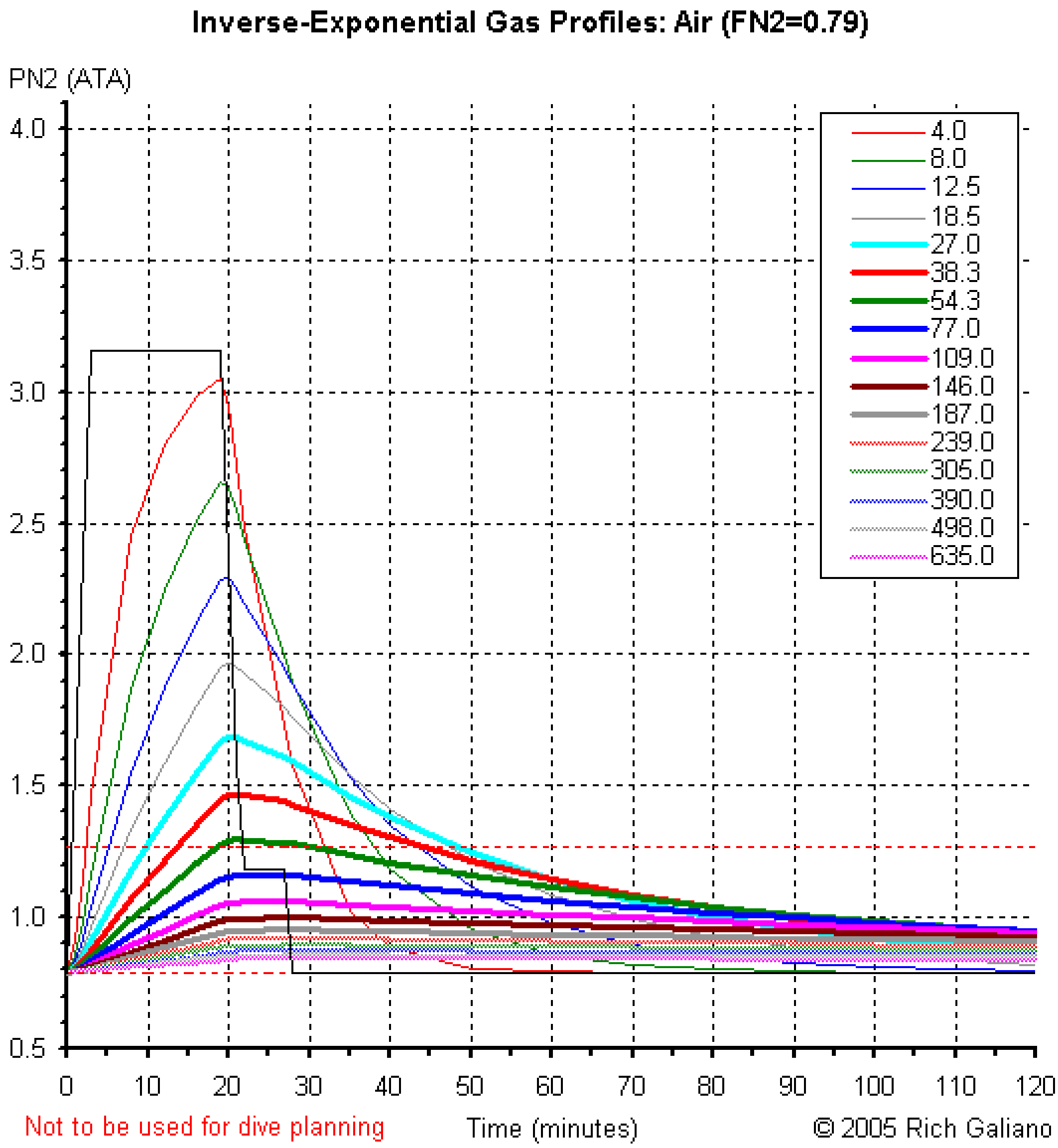
The five slowest compartments (239.0 - 635.0, stippled lines) pick up so little nitrogen loading that even at t=60 they have not achieved a pressure ratio of 1.6:1 with respect to surface pressure. They would therefore seem to present little concern for decompression in this example.

However, the seven middle compartments (27.0 - 187.0, heavy lines) all become significantly nitrogen-loaded, and off-gas slowly enough that even at the end-time of this plot (t=120) they all still contain more than the "safe" pressure ratio of 1.6:1. In Buehlmann's model of decompression, it is typically these compartments that control decompression schedules for real-world dive profiles.

Typically, in real decompression schedules, the fast compartments off-gas well within the times required for the middle compartments, while the slow compartments seldom enter into the equation. Perhaps less intuitive is the fact that the heavily-loaded fast compartments may still influence the early part of an extended decompression schedule ("deep stops") before yielding control to the middle compartments. Slow compartments may affect "time to fly" considerations.

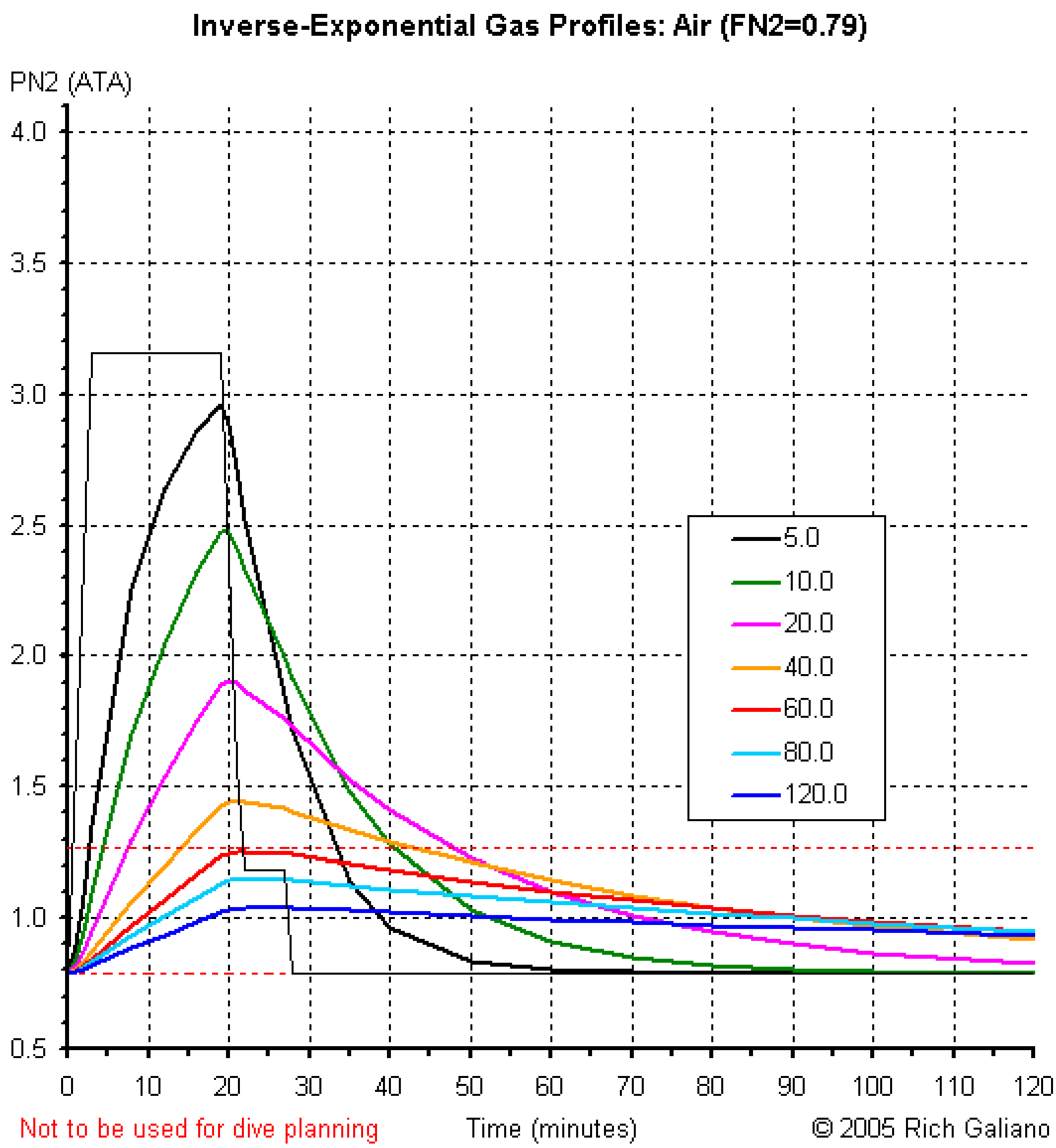
It is also worth noting that off-gassing is a much slower process than on-gassing, as evidenced by the fact that after an equal time of on-gassing and off-gassing, only the two fastest compartments have returned to their original state; all others still contain significant nitrogen loads.

One might also conclude from this presentation that short "bounce dives" of around 5 minutes duration should be relatively safe, since only the fast compartments acquire any significant nitrogen loading, and this can be off-loaded with a brief deco stop or even just a slow ascent. Alas, that is not the case though, as real-life is a lot more complicated than this simple plot.



What would the nitrogen pressure curves look like for a more realistic dive profile? Above is a profile taken directly from the PADI Recreational Dive Planner: 100 ft for 19 minutes, with a 5 minute safety stop at 15 ft. Ascents and descents are crudely modeled in 1 ATA steps. It becomes clear from this plot that for relatively short, no-decompression dives, the very long compartments of Buehlmann's model are essentially irrelevant - they never reach a high enough pressure to matter. PADI came to this conclusion as well: their model is based on 7 tissue compartments with half-times from 5 to 120 minutes.

Another point here concerns surface intervals. After 30 minutes, or t=60, several compartments still show significant nitrogen loading. After about 60 minutes, or t=90, all have dropped down to fairly low levels, with little improvement at 90 minutes (t=120). This would suggest that a surface interval of around 60 minutes is optimal; shorter is not enough, and much longer is simply a waste of time.



The same profile calculated with the seven tissue compartments of PADI's RDP.

A quick calculation of pressure ratios will demonstrate that according to this graph, the diver will leave the water with a worst-case pressure ratio of about 2.0, or probably bent. That just goes to show that decompression modeling is much more complex than what is depicted in these crude graphs. The PADI RDP has a proven track record of safety. PADI, the US Navy, and others went through reams of real-life data, tweaking, adjusting, testing, and retesting their models. They didn't just crank out a few simplified equations and call it a day, like I have here.

Most dive computers that utilize Haldane's method use nine to twelve tissue compartments, rather than the full 16 of Buehlmann's model. There are a number of other decompression models besides Haldane's. Some are quite complex and curious. Bubble models concentrate on the physical formation and growth of gas bubbles, while the latest Navy method takes a purely statistics-based approach, and makes no attempt to model any physical process at all. In the end though, they all share one thing: they all tweaked to fit real-world data on scuba diving. Is one model better than another? Given that they all "cheat" in the end to get the right answer, I would say probably not.

Decompression Theory 3

There is nothing mystical about decompression theory. In fact, it is all rather straightforward. For example, here is the Buehlmann ZH-L16A decompression algorithm (er, I mean the *Modified Haldane algorithm*; see below) as described previously, implemented in Microsoft Excel. In addition, versions B and C of the algorithm are also presented. If you have not already done so, you should read this excellent explanation of Haldane's decompression algorithm before proceeding.

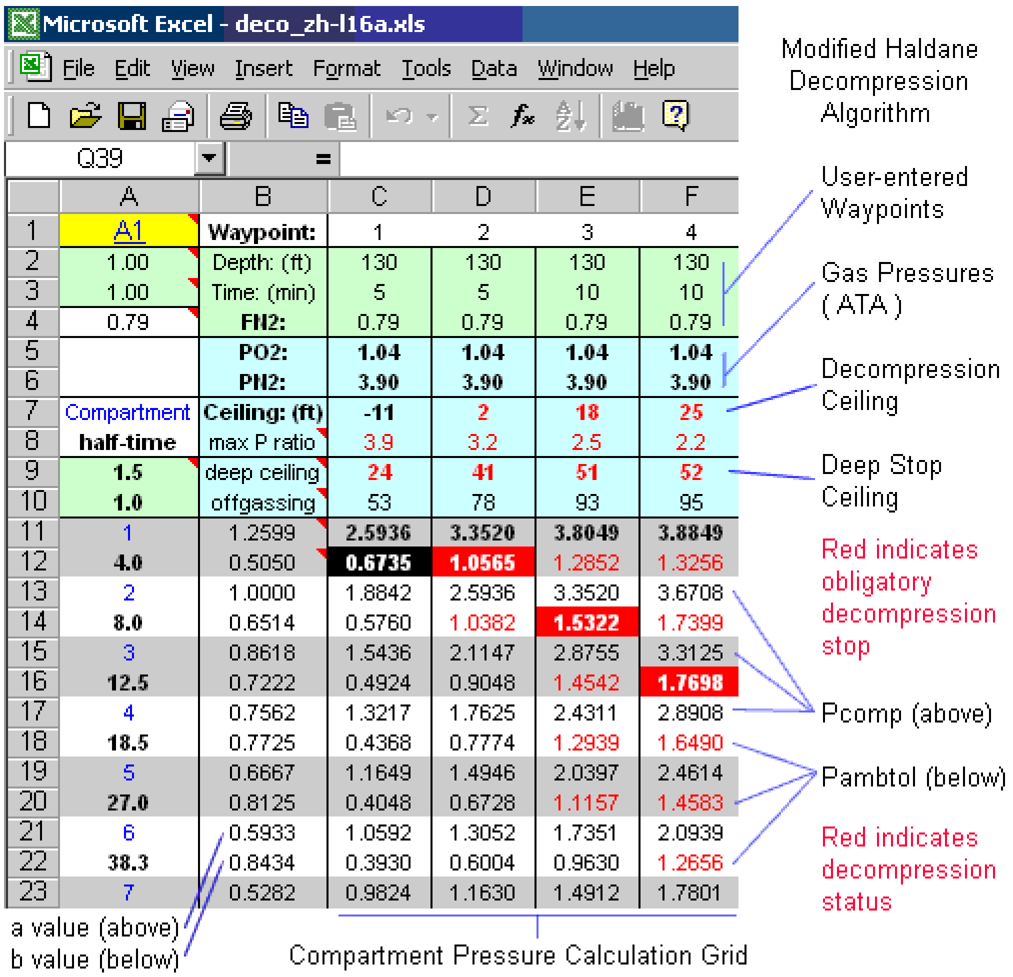
Note to new divers and potential new divers:

This information is presented for general interest. Don't be scared off by what you see here - you don't need to learn any of this to become a safe and competent scuba diver. You will however need to understand dive planning.

Warning:

This software should not be used for the planning of actual dives ! This implementation of the modified Haldanean decompression algorithm is extremely rudimentary and is suitable for educational purposes only.

This software has received no scientific testing or validation. This software may contain bugs, and the figures which it outputs may be erroneous. The schedules which it generates are simply the results of mathematical calculations which do not in any way represent the mechanics of the human body. Do not use this software in situations where failure of the software may lead to illness, injury or death. The designers of this software accept no responsibility for illness, injury, loss or death of the user or any third party.



	A	B	C	D	E	F
1	A1	**Waypoint:**	1	2	3	4
2	1.00	Depth: (ft)	130	130	130	130
3	1.00	Time: (min)	5	5	10	10
4	0.79	**FN2:**	0.79	0.79	0.79	0.79
5		**PO2:**	**1.04**	**1.04**	**1.04**	**1.04**
6		**PN2:**	**3.90**	**3.90**	**3.90**	**3.90**
7	Compartment	**Ceiling: (ft)**	**-11**	**2**	**18**	**25**
8	**half-time**	max P ratio	3.9	3.2	2.5	2.2
9	**1.5**	deep ceiling	**24**	**41**	**51**	**52**
10	**1.0**	offgassing	53	78	93	95
11	1	1.2599	**2.5936**	**3.3520**	**3.8049**	**3.8849**
12	**4.0**	0.5050	**0.6735**	**1.0565**	1.2852	1.3256
13	2	1.0000	1.8842	2.5936	3.3520	3.6708
14	**8.0**	0.6514	0.5760	1.0382	**1.5322**	1.7399
15	3	0.8618	1.5436	2.1147	2.8755	3.3125
16	**12.5**	0.7222	0.4924	0.9048	1.4542	**1.7698**
17	4	0.7562	1.3217	1.7625	2.4311	2.8908
18	**18.5**	0.7725	0.4368	0.7774	1.2939	1.6490
19	5	0.6667	1.1649	1.4946	2.0397	2.4614
20	**27.0**	0.8125	0.4048	0.6728	1.1157	1.4583
21	6	0.5933	1.0592	1.3052	1.7351	2.0939
22	**38.3**	0.8434	0.3930	0.6004	0.9630	1.2656
23	7	0.5282	0.9824	1.1630	1.4912	1.7801

Click image to download spreadsheet.

User-enterable dive **waypoints** and conservatism factors make up the green cells in the sheet. Each waypoint triplet represents a segment of a dive:

- depth (feet, bold red indicates decompression violation)
- time at depth (minutes)
- fraction of Nitrogen in the breathing gas (0.79 = air)

Fill in your dive profile starting with waypoint 1 and using as many as you need. Unused waypoints can be cleared. All dives are assumed to begin at sea level and breathing air (FN2 = 0.79) and are assumed to be conducted in saltwater.

Cells A2 and A3 are user-enterable **scale factors** for the a and b values. Entering values less than 1.00 here will cause the allowable pressure calculations to back off from the theoretical limits, making the algorithm more conservative. The default values are 1.00 - least conservative. Cell A9 is the maximum deep-stop pressure ratio. Cell A10 is a dummy - you can use it for a dive sequence number if you like.

The blue cells show the cumulative results of the previous and current waypoints:

- **PN2** and **PO2** are the partial pressures of oxygen and nitrogen at the current depth and gas mix. This is not strictly part of the algorithm, but is presented to assist in selection of Nitrox mixes.

- **Ceiling** is the decompression ceiling at the end of the current waypoint, or the minimum depth that can be ascended to at the next waypoint. Negative ceilings are above sea level (see below.)

- **Max P ratio** is the worst-case compartment pressure ratio that would result from ascending to the ceiling depth.

- **Deep Ceiling** is the deep-stop decompression ceiling at the end of the current waypoint, based on the limiting pressure ratio selected in cell **A9**.

- **Offgassing** is the minimum depth at which at least one tissue compartment is offgassing, even if others may still be on-gassing.

Below each waypoint is the column of calculations for the theoretical tissue compartments. For each compartment, the partial pressure of nitrogen is shown above, and the minimum tolerable ambient pressure is shown below. Results displayed in red indicate that decompression will be required at the next waypoint. The maximum values for each column are bolded, while the controlling compartment for each waypoint is picked out with reverse colors.

The formatting of the intermediate calculations allows the internal workings of the algorithm to be easily inspected. Changes in compartment pressures at each waypoint are displayed, and the shifting of the controlling compartment is visually obvious, especially when long duration dives or surface intervals are broken up into short equal-depth waypoints.

Pulmonary Oxygen Toxicity units (OTU, at the bottom of the sheet) is not part of the decompression algorithm, but is a simple calculation that is easy to implement in the spreadsheet, and so is included here as an afterthought. BSAC recommends limiting oxygen exposure to 800 OTU / day. CNS oxygen toxicity is not calculated.

Example:

The spreadsheet is already "seeded" with some interesting waypoint data. The waypoints are as follows:

Waypoints 1-5:	An outlandish decompression dive to 130 feet for 50 minutes on air. This is broken up into five segments to show the on-gassing of the 16 compartments over time.
Waypoints 6-8:	Voluntary deep stops at 60 and 50 feet on air for two minutes each. Note that by the regular deco algorithm, an ascent directly to 40 feet is allowed,

	but this would incur a very high worst-case compartment pressure ratio, and should therefore be avoided.
Waypoint 8:	Obligatory decompression stop at 40 feet for two minutes on air.
Waypoints 9-11:	Obligatory decompression stops at 30, 20, & 10 feet for a total of 29 minutes, on 80% O2 Nitrox decompression mix. Note that these stops are following the "normal" decompression ceiling rather than the deep stop ceiling.
Waypoint 12:	Surface interval of 2 hours
Waypoint 13:	A no-decompression dive to 90 feet for 40 minutes on EAN36 or 36% Nitrox
Waypoint 14:	Five minute safety stop at 15 feet on EAN36
Waypoint 15:	24 hour time-to-fly interval
Waypoint 16:	2-1/2 hour airplane flight at a cabin pressure of 8000 feet (typical airliner)

Following the usual practice, the obligatory deco stops (waypoints 8-11) are rounded up to the next ten foot depth. Therefore, a decompression ceiling of 30 feet at waypoint 7 results in a decompression stop of 40 feet. for waypoint 8. The time at waypoint 8 is then adjusted to result in the deepest possible ceiling above 30 feet, the next intended deco stop. This process is continued until the ceiling becomes 0 or negative, at which point it is safe to ascend to the surface. One could also follow the deep-stop schedule all the way to the surface, but that would take much longer.

You may notice that the 50 foot stop slightly violates the deep stop requirements, and really should be three minutes instead of two. However, making all the deep stops the same is a nice simplification for the real dive. You could just as well make all the deep stops three minutes for added conservatism, or 2-3-2 if you are really fussy, but in my opinion that would be placing a great deal of weight on the precision and accuracy of a model that is inherently rough at best. Perhaps the real point of all this is to show that good common sense and understanding are more important than blind reliance on any mathematical model, whether it is this one or the one in your dive computer !

Deep Stops

Recall that Haldane originally postulated that a "compartment" could undergo a

later revised down to 1.6. Therefore the limiting pressure ratio of 1.5 (cell A9) for the deep-ceiling calculations is somewhat conservative. Note that many of the maximum pressure ratio values are considerably greater than this: a fast ascent to the theoretical ceiling depth of two feet at waypoint three would result in a worst-case compartment pressure ratio of **3.2** - approximately the same as a can of soda (that's pop, for you midwesterners.) and would very likely result in arterial bubbling and bends, even though it is completely within the accepted decompression model !

The purely mathematical ZH-L16A algorithm was found to be inadequate for real-world use, and so was developed into the more conservative ZH-L16B and ZH-L16C algorithms, which are also presented. ZH-L16B was developed for dive table calculations by empirically tweaking some of the a-values. ZH-L16C was developed in the same way for use in real-time dive computers, and is more conservative again.

As you can see, the spreadsheet does pretty much everything your dive computer can do, and then some. Nitrox is automatically handled, as are repetitive dives, gas switches, user-selectable conservatism, and high altitude diving. However, rather than giving you a complete decompression schedule for your dive, the spreadsheet merely indicates the ceiling for the next waypoint, based on the allowable overpressure of the current waypoint. This can be used to work out a staged decompression schedule by hand, as I have done in the example. Similarly, the user may incorporate waypoints for deep stops, air breaks, surface intervals, and even time-to-fly.

Ascents and descents are assumed to be instantaneous - not very realistic. These could instead be modeled using very short waypoints at intermediate depths. A real dive computer probably computes a new waypoint several times a minute, and so automatically handles transients like this. You could do the same in the spreadsheet, but it would use up the available waypoints pretty quickly.

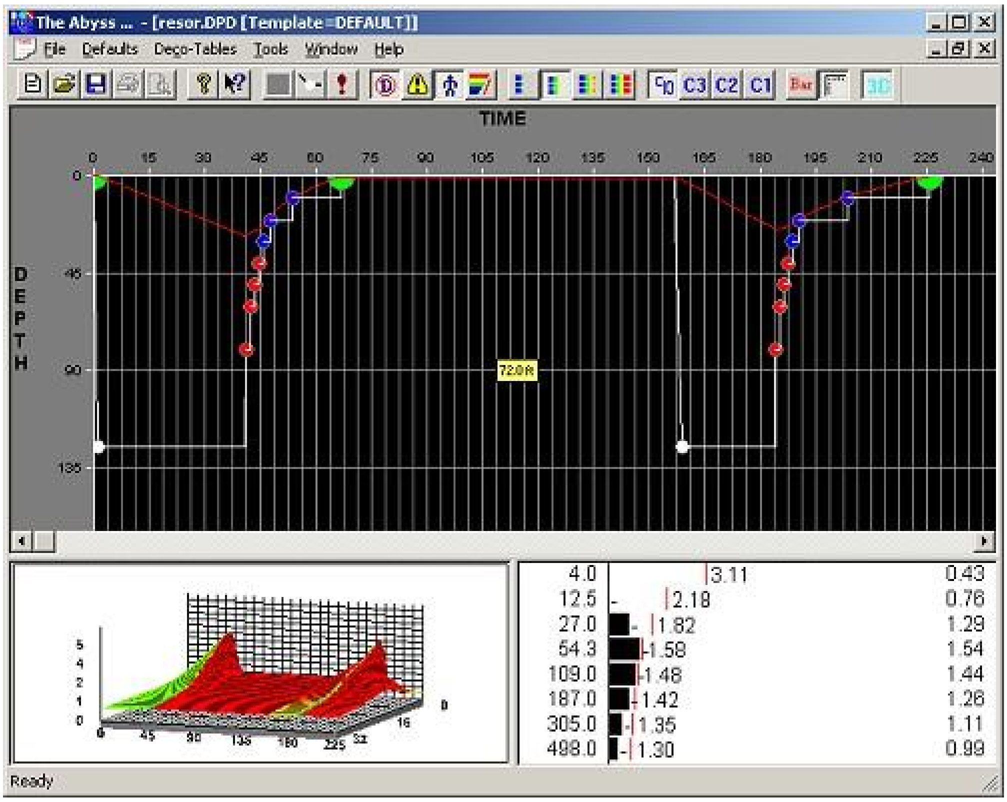
In fact, there is no reason that the spreadsheet could not have hundreds of waypoints, except that it would become very large and difficult to display, and sixteen points is more than enough for expositional purposes. A much more efficient way of handling hundreds or thousands of waypoints would be to only retain the result of the last set of calculations, as a real dive computer would do. This sort of dynamic programming could be implemented in the spreadsheet as well, using a macro. But that would defeat the purpose of this entire exercise, which is to display the inner workings of the decompression algorithm. Trimix would be handled similarly, and I have done it also, but I will not go into the details.

For simplicity, all dive profiles are assumed to begin at sea level breathing air, although altitude diving would be easy to implement. In fact, you can do this yourself by setting the first waypoint to the desired altitude for a very long time (10,000 minutes should do the trick.) Then just make sure your last waypoint will allow you to ascend to the same altitude. Altitudes above sea level are expressed in feet of water here:

+1000 feet of air = approximately -1 foot of water.

Try setting up some dive profiles of your own, and compare them with dive tables and your own computer. Set up profiles and surface intervals in increments, and watch how the controlling compartment changes during on-gassing and off-gassing. The profiles you generate here will probably be less conservative than what you will get from a real dive table, but should be in the ballpark. And as I said -

DO NOT USE THESE RESULTS FOR REAL DIVE PLANNING !



Abyss - a real decompression program

Buehlmann's is the simplest decompression algorithm, based on Haldane's ideas. For copyright reasons, most dive software and computers claim to use a Modified Haldane model, which is in fact modified to be Buehlmann's. There are other decompression algorithms as well, such as VPM (Variable Permeability Model) and RGBM (Reduced Gradient Bubble Model.) These algorithms model decompression based on bubble formation, and are much more complex and computationally intensive than Buehlmann's. If you would like to try one of these, I suggest V-Planner, which is a free download.

The interesting thing is that all these algorithms, regardless of exactly what they are modeling, generate surprisingly similar schedules, which in the end must all agree with the same empirical data. In fact, most algorithms, including the one shown, are actually tweaked to agree with the empirical data. Some people will dicker over minor variations, but the truth is that decompression calculations are imprecise by nature, and real-world decompression is subject to many other factors, many of which are simply unpredictable.

It is my own feeling that the apparent precision of each algorithm, and the small differences between them, are completely overwhelmed by random real-world factors. This renders the choice of algorithm inconsequential, and makes them all somewhat suspect. It is far too easy to look at the complexity of any calculation, and the number of decimal places that a modern computer will carry and display, and get the impression that the result is extremely accurate when in fact it is not.

The term "undeserved hit" is used to describe cases where a diver did nothing wrong, whether it be by tables or their dive computer, and got bent anyway. Such things happen, and always will. In the end, decompression is still a statistical science, and no model is 100% correct. Given all the unknowns and uncertainties, the best way to be safe is to keep the modeling simple and the calculations error-free, and dive the resulting schedules conservatively, with voluntary deep stops and extended hang times, especially at the shallow end.

I have also developed a version of this spreadsheet for Trimix, Heliox, and other mixes. That algorithm is computationally much more complex, requiring four interlinked sheets where the Nitrox/Air version used only one. Building this complexity into a dive computer is clearly no easy task - the majority of Trimix dive computers that have been released over the years have proven to be buggy if not outright flawed. I myself would not trust one.