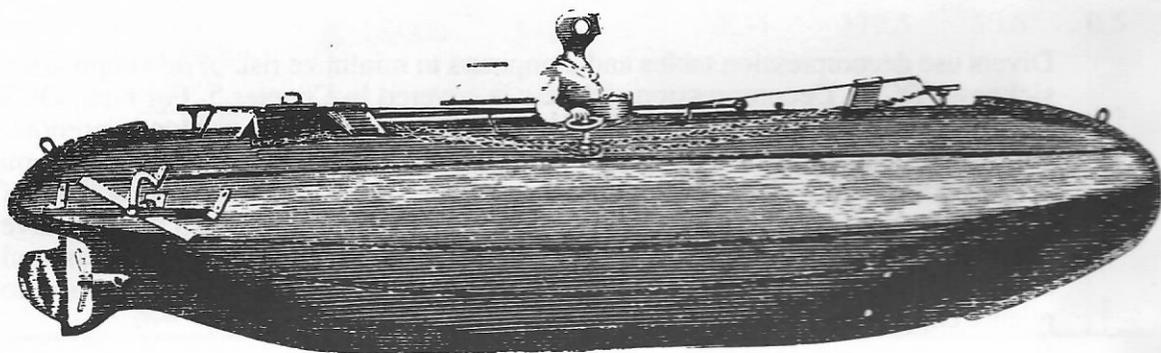


# CHAPTER 1

## DECOMPRESSION TABLES AND COMPUTERS



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This book begins with the complex subject of decompression tables and computers because of high interest by divers. This chapter surveys basic concepts and terms, which can help you make diving decisions to reduce risk of decompression sickness. The chapter does not detail specific decompression tables and computers, nor make recommendations for particular models. Understanding their fundamentals will help you make your own decisions. Topics are from questions divers ask most frequently, and from common misconceptions. Because of large demand, numbers and equations are explained conceptually so all can enjoy, even without a background in math.

Understanding of decompression theory is still incomplete, and more involved than explained here, but begins with these basics.

- Brief Review of Pressure
  - Where Decompression Tables And Computers Come From
  - Basic Terms & Concepts
  - Introduction to Non-Haldane Decompression Models
  - Diving With Gases Other Than Air
-

## CHAPTER 1 PART I

### BRIEF REVIEW OF PRESSURE

---

Divers use decompression tables and computers to minimize risk of decompression sickness (DCS). Decompression sickness is covered in Chapter 5. For now, DCS results from extra inert gas, usually nitrogen, forming bubbles in blood and other areas of your body after ascent. The source of nitrogen is the pressurized air you breathe from your scuba tank or other air supply during a dive. The goal of decompression computation is to determine how long and how deep you can dive without undue risk of DCS after ascent. It also determines if you can ascend directly to the surface, or need to stop during ascent before reaching the surface, to release enough dissolved nitrogen so it doesn't become bubbles.

- Ambient Pressure
  - How Nitrogen Gets In And Out Of Your Body
- 

#### AMBIENT PRESSURE

*Ambient Pressure – Surrounding Pressure. On land, exerted by the weight of air above you. Under water, by both atmospheric and water pressure. As distance down increases, pressure increases.*

*With sea level as a zero starting point, pressure under water, or in a tank, is called gauge pressure and does not include atmospheric pressure (14.7 psi, 760 mmHg, or 101.3 kPa). When including atmospheric and water pressure together, it is called absolute pressure.*

In the near vacuum of space, there is just about no air and no air pressure. On land, the atmosphere around you exerts pressure on your body. The pressure is from the weight of miles of air above you. It doesn't take much effort to draw a breath of air. The pressure of your air supply is external, or ambient pressure.

With depth underwater, pressure continues increasing from the combination of air and water pressure. Water weighs more than air. You don't have to go very deep before ambient pressure is considerably higher than at the surface. If you've ever tried to breathe under water through a long snorkel or tube extended to the surface, you know this doesn't work past a few feet. You can't expand your chest against the overpowering ambient pressure.

Your scuba regulator avoids this problem by sensing ambient pressure. It delivers air to your mouthpiece at ambient pressure, making breathing possible. You breathe air at greater than atmospheric pressure. This higher-than-normal air pressure is the source of decompression problems.

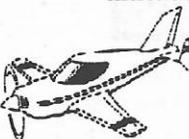
|   | Distance |        | Absolute Pressure |       |       |     |
|---|----------|--------|-------------------|-------|-------|-----|
|   | Feet     | Meters | psi               | mmHg  | kPa   | atm |
| altitude<br>     | 18,000   | 5486   | 7.34              | 379.5 | 50.6  | 0.5 |
|   | 10,000   | 3048   | 10.11             | 522.6 | 69.7  | 0.7 |
| sea level<br>    | 0        |        | 14.7              | 760   | 101.3 | 1   |
| under water<br> | 33       | 10     | 29.4              | 1520  | 202.6 | 2   |
|   | 66       | 20     | 44.07             | 2280  | 303.9 | 3   |

Figure 1.1. As you go up, pressure decreases. As you go down pressure increases. Pressures underwater are for sea water. Fresh water values are slightly less.

### HOW NITROGEN GETS IN AND OUT OF YOUR BODY

*Uptake - Transfer of dissolved gas into the body. Also called ongassing or ingassing.*

*Elimination - Transfer of dissolved gas out of the body. Also called offgassing or outgassing.*

Nitrogen is the inert gas most commonly considered in decompression theory. Nitrogen in the air you breathe from your scuba tank or other air supply passes from your lungs to blood vessels in your lungs. Nitrogen changes from gaseous to dissolved form. Dissolved nitrogen travels with your blood to your body tissues. Other inert gases behave similarly. The process of absorbing dissolved nitrogen into your body tissues is called nitrogen uptake, also called ongassing, and ingassing.

Overall movement of gas molecules during ongassing is from areas of higher concentration and pressure to lower concentration and pressure, from lungs to blood to body tissue, Figure 1.2.

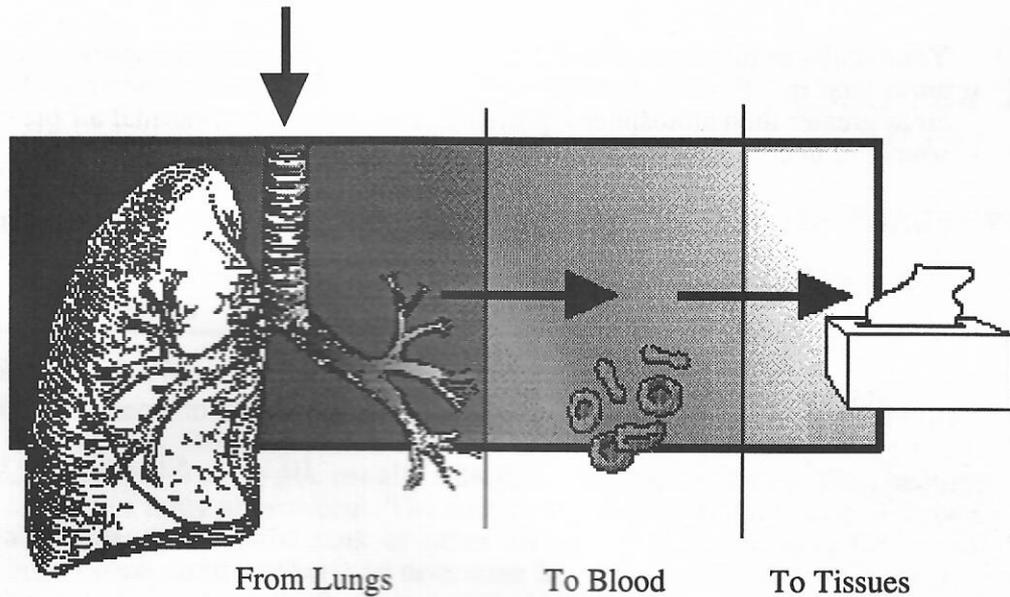


Figure 1.2. Overall movement of gas molecules is from areas of higher concentration and pressure to lower concentration and pressure, from lungs to blood to body tissues.

Greater pressure with increasing depth dissolves more gas. This is a fundamental principle of chemistry summarized by Henry's Law. As you dive deeper, your regulator increases the pressure of the air you breathe to match ambient pressure, so you can breathe. The deeper you go, the more nitrogen from each breath dissolves in your body. The longer you stay, the more time nitrogen has to dissolve.

When you ascend, an opposite chain of events occurs. Ambient pressure decreases as you get shallower. Your regulator reduces the pressure of your air supply to match decreasing ambient pressure. Ambient pressure becomes less than your accumulated internal nitrogen pressure. Nitrogen in your body begins coming back out of you. Nitrogen transfers first from your tissues to your blood, then from your blood back to your lungs where you breathe it out. This elimination process is called offgassing or outgassing. What we hope happens is that nitrogen remains dissolved in the blood until it gets to the lungs without reforming into gas. This is not always the case.

Nitrogen can come out of solution to become a gas again before it gets to your lungs, if your internal nitrogen pressure exceeds a maximum amount relative to ambient pressure, during or after ascent. Gaseous nitrogen forms tiny bubbles that are accepted to be the basis of decompression problems.

## CHAPTER 1 PART II

### WHERE DECOMPRESSION TABLES COME FROM

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This section gives a brief history of decompression theory, and summarizes what most current decompression tables do.

- History
  - Modern Practice
  - What Decompression Tables And Computers Calculate
- 

#### HISTORY

Illness from pressure change was first recorded in the late 1600's by physicist and chemist Robert Boyle, who exposed animals to changes in pressure. One of his more famous observations, among many, was a gas bubble in the eye of a snake when he lowered pressure in a vacuum chamber. In other work, he explained change in gas volume from change in pressure, summarized by Boyle's Law.

The first description of pressure-related illness in humans was in 1841 by Triger, before modern scuba was invented. Laborers worked in mines and under bodies of water, in pressurized tunnels and water-tight boxes called caissons. The tunnels and caissons were pressurized with air to keep water and mud out. As work progressed deeper, workers began breathing air at greater pressures, and returning to the surface with pain and sometimes paralysis. Triger wrote of limb pain, and described the treatment – alcohol applied externally and internally. Later, during construction of the Brooklyn Bridge and other bridges, the bent over posture to ease pain from this “caisson disease” popularized the name “the bends.” More than a hundred workers suffered serious bends during the Brooklyn bridge construction from 1869 to 1883.

Several researchers participated in unraveling a series of issues to explain this disease, where Pol and Wattle noted in 1854, “One pays only upon leaving.” By 1878, French physiologist Paul Bert had determined the connection between bends and nitrogen bubbles, and showed that pain could reverse with recompression. The British Royal Navy needed to minimize decompression sickness among fleet divers, and commissioned John Scott Haldane and co-workers Arthur E. Boycott and British naval officer Guybon C. Damant. In 1908, they published their work along with three sets of tables of time and depth schedules. These tables were adapted and used by the British Royal Navy and the United States Navy.



According to Haldane:

- Different areas of your body absorb and release nitrogen at different rates.
- Rates of nitrogen absorption and elimination can be estimated using a fairly easy mathematical equation. The equation is exponential, which means that each area gains (or loses) a fixed percentage of how much it has left after every passing unit of time. See the glossary for explanation of exponentials.
- A diver could ascend without decompression problems so long as pressure reduction was not by more than half.

### MODERN PRACTICE

Most dive tables and computers currently used by divers are based on concepts initiated by Haldane, and added to by followers. Most do the same four things, explained next in Part III, Terms and Concepts:

- They estimate the partial pressure of inert gas, usually nitrogen, that would accumulate in different body areas, handled computationally as “compartments”.
- They compare estimates of internal nitrogen partial pressures to their supposed maximum tolerated pressures, usually called M-values.
- They state depth and time limits on ascents so you don’t exceed these maximums in any compartment. Pressure reduction may be more or less than the half originally proposed by Haldane.
- If compartments would exceed their M-values on ascent, they tell the diver to make a decompression stop, to let compartments drain down until they are below M before ascending further.

### WHAT DECOMPRESSION TABLES AND COMPUTERS CALCULATE

It is said that some divers believe that the decompression computer worn on the body somehow measures nitrogen in the body. Decompression computers, like tables, do not measure the nitrogen, they estimate it through calculation. Most decompression tables and computers currently used by divers use the same base equation derived by Haldane, modified by number and speed of compartments selected for the model, and compare it to what different modelers select as the maximum amount of nitrogen each compartment can hold on ascent.

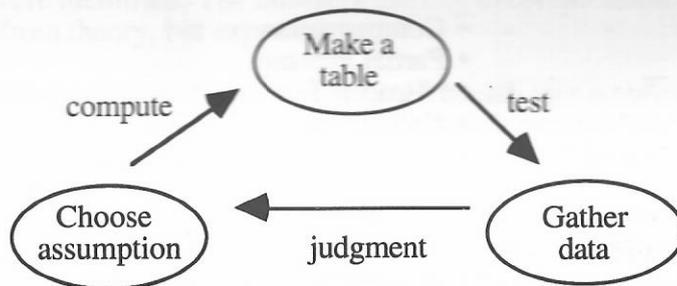
The equation for Haldane-based computation has several parts, explained next in Part III:

- How much gas partial pressure you start with already in your body
- Pressure around you at each depth, and how long you stay there
- Percentage of nitrogen, or other inert gases, in your breathing gas

- Partial pressure of nitrogen in each compartment at each depth, which is determined by the percentage of nitrogen and depth.
- Speed of gas uptake and elimination in each compartment (half-times)
- Maximum amount of nitrogen each compartment is thought to tolerate upon ascent, called M-values.

The final formula, or algorithm, defines the model and is often proprietary information. We don't yet have algorithms that exactly match what is thought to be happening in the body.

Decompression tables and computers are not just number fiddling. Decompression algorithms are tested on divers. The equations are then modified where needed, to reflect, as much as possible, data found during diving.



Reports exist of divers turning off their computer between repetitive dives so the computer will allow them more time on the next dive, or hanging it over the side of the boat after a dive if it says they should not yet surface. These are good ways to get expensive trips to a medical facility for decompression sickness treatment. Use your computer only as directed in the instructions.

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“Hello, I am a decompression model.  
I will tell you what you tell me to tell you.”

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## CHAPTER 1 PART III

### BASIC TERMS & CONCEPTS

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This section summarizes the sometimes mysterious vocabulary of decompression science. Understanding these basics helps understand decompression in general, the Haldane-based tables mentioned in Part III, the non-Haldane tables introduced in Part IV, and use of gas mixtures other than air, Part V.

- Compartments
  - Partial Pressure
  - Nitrogen Tension
  - Half-times
  - Fast and Slow Compartments
  - Saturation
  - Supersaturation
  - Supersaturation Ratios
  - M-Values
  - Table-Based and Model-Based Computers
- 

#### COMPARTMENTS

*In anatomy, tissues are body areas that are structurally and cellularly similar, for example, muscle tissue.*

*In decompression, compartments are areas similar in rate of inert gas uptake. They are sometimes called "tissues" but compartment is preferred because they are not specific anatomic entities.*

Your entire body absorbs nitrogen under pressure. Some body areas absorb gas faster than others, for example, 5 and 10 minute compartments, compared to 60 and 120 minute compartments, further explained in the section on half-times.

Contemporary researchers prefer the term compartment rather than tissue, since decompression compartments are not whole body tissues like muscle or nerve. Because so many divers and researchers use the term tissue, confusion sometimes results. Anatomically, there are only four tissues in the human body: muscle, connective, epithelial, and nervous tissue. Everything in your body is made of combinations of those four. For decompression work, the body is divided computationally into any number of compartments. How many is up to the modeler.

- Muskel
- Bindegewebe (Stützgewebe)
- Epithel (ep. innerer Gewebe)
- Nervengewebe Haut



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Even though decompression compartment divisions do not correspond one to one with anatomic tissues, they reference existing areas (theoretically) wherever they might be, that behave alike.

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Although blood flow may change with activity or other events in the body, thereby changing an anatomic tissue's speed, decompression models account for many compartments, which we hope account for most of the possibilities. At least one dive computer so far, the Uwatech (Bühlmann) Aladin "Air-X," tries to deal specifically with changes in blood flow due to exercise (determined by air consumption) and cold.

**Compartment Identifying Experiments.** Divers often ask how the different compartments were identified. The numbers naming decompression compartments derive not only from theory, but experiment.

If you came up from a dive and breathed out each breath into a collection bag for a set time and analyzed the gas, you could find how much nitrogen you released from your entire body. If you put dots on a chart showing how much nitrogen came out every few minutes, it would draw a particular type of curve called an exponential curve, which means that you lost a fixed percentage of the resulting value with every passing unit of time (see the glossary for explanation of exponentials). This, more or less, estimates a measurement called total body nitrogen washout. Total washout curves, like most composite descriptions, don't tell how much nitrogen came from different parts of you, just an average amount over all. You wouldn't have information about washout rate in your different compartments.

Decompression researchers use many techniques to try to identify how fast specific areas of your body ongas and offgas. Some experiments measure blood flow to different parts and draw inferences about how much gas will be carried to them. This method is limited by the fact that blood flow is only part of how different amounts of gas wind up in your anatomic tissues. Some work takes a different tack by putting a radioactive marker on nitrogen introduced into specific areas, then determining how much goes in and out. Other work identifying different speed tissues came from Naval submarine work. Escapes from submarine towers after short, deep exposures, and experimental dives with longer decompression using regular compressed air, showed certain washouts proceed faster than others.

**Multi-Compartment Models.** Different compartments take up nitrogen at different rates. Each compartment also tolerates a different amount of nitrogen before it accumulates too much to ascend directly to the surface without stopping to let some out. By including several compartments, decompression tables and computers are thought to do a better job of accounting for the various areas of the body.

Multi-compartment decompression tables and computers limit your time underwater so no one compartment gets too much. Almost all decompression tables and computers are multi-compartment models.

## PARTIAL PRESSURE

*Partial Pressure – The part of total pressure exerted by only one gas in a mixture of several gases. All the partial pressures together make up total pressure. Partial pressure of a gas is the total pressure times the fraction (percentage) of that gas. Partial pressures determine how much inert gas you will take up and eliminate.*

Understanding partial pressure is an important part of understanding decompression. Spend some time to get familiar with this section, if you aren't already.

On land, the weight of the air column above you presses on you. Nitrogen makes up about 78% of air, so nitrogen exerts about 78% of the pressure. That's why it's called a partial pressure. Another 21% of the pressure on you comes from oxygen. The sum of all the partial pressures equals the total pressure. That is Dalton's Law. Argon makes up almost 1% of the pressure, and is usually lumped with nitrogen and tiny amounts of helium, neon, krypton, xenon, and others to give 79% inert gas in decompression calculations.

Partial pressure of nitrogen is commonly abbreviated  $PN_2$  (pronounced pee-enn-tu). Sometimes  $pPN_2$  is used, particularly in engineering.  $FO_2$  is partial pressure of oxygen. *it is:  $PO_2$*

You may occasionally see the expression  $FiO_2$ , (pronounced eff-eye-oh-tu), rather than just  $FO_2$ .  $FiO_2$  means the fraction of inspired oxygen. That is different from what you breathe back out, which is the fraction of expired  $O_2$ , written  $FeO_2$  (eff-eee-oh-tu). Usually  $FiO_2$  is inferred when you see  $FO_2$ .

---

### Partial Pressures Of Gases In Air

The sum of partial pressures = total pressure

|   |             |                       |
|---|-------------|-----------------------|
| nitrogen                                      | 0.78        | (just over 78%)       |
| oxygen  | 0.21        | (just under 21%)      |
| argon, carbon dioxide,<br>water & trace gases | 0.01        | (around 1%)           |
|   | <u>1.00</u> | atmosphere abs 100% ✓ |

---

**Partial Pressure Determines Gas Exchange.** Partial pressure of nitrogen in your breathing mixture determines how much nitrogen you ongas and offgas. As  $PN_2$  of the air you breathe increases with depth, nitrogen ongassing increases. When you reduce water pressure around you by ascending, nitrogen pressure that you have built up in your body then exceeds the  $PN_2$  of water around you. You offgas nitrogen.

**Units of Partial Pressure.** There are several units for partial pressure. Figure 1.1 shows relative scale of a few common units.

Medical people often measure partial pressure in millimeters of mercury (mmHg). For decompression, the unit of partial pressure is often atmospheres absolute (ATA or atm abs), defined in Part I. Calculations using atmospheres are simple and relate easily to diving because they compare to total sea level pressure at one ATA. For example,  $PO_2$  at the surface is 0.21 ATA, because air is 21% oxygen.  $PN_2$  of regular air with 79% nitrogen is 0.79 ATA at the surface.

In scientific applications, the term "atm abs" or the International System (SI) pressure units pascals (Pa) and kilopascals (kPa) are preferred over "ATA." The term ATA may also be confused with the technical atmosphere sometimes used in Europe, abbreviated "at," or if absolute "ATA." In this chapter, ATA is used because you will see it so commonly. The glossary further explains atmospheres, atmospheres absolute, technical atmospheres, and the SI system and units. A table of pressure conversions is in the Appendix.

**Interesting Note.** Because the term ATA stands for atmospheres absolute, and is already plural, the term is ATA, not ATAs.

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$PN_2$  of regular air with 79% nitrogen is 0.79 ATA at the surface.  
 $PO_2$  of regular air with 21% oxygen is 0.21 ATA at the surface.

---

**Fraction of Gas Does Not Change With Depth.** Composition of any breathing gas does not change with depth, just the pressure on it. The percentage of oxygen stays 21% for regular air, and nitrogen stays 79%, so  $FO_2$  stays 0.21 and  $FN_2$  stays 0.79. The fraction only changes if you change the mix (Part V).

**Partial Pressure Changes With Depth.** When you dive to 33 feet (10 m), or two atmospheres absolute, you are under twice the total pressure than at the surface at one atmosphere absolute. Doubling total pressure doubles the partial pressure of oxygen in regular air from 0.21 to 0.42 ATA, and  $PN_2$  from 0.79 to 1.58. Tripling pressure by diving to 66 feet triples  $PO_2$  to 0.63 ATA.

Once you know total pressure, you can calculate partial pressure. For depths that are not convenient multiples, find absolute pressure by dividing the depth in feet by 33, then adding 1. The 1 is for atmospheric pressure, which is part of absolute pressure:

$$\frac{D}{33} + 1 \quad \text{so, at 100 feet: } \frac{100}{33} + 1 = 4.03 \text{ ATA (or atm abs)}$$

**Calculating Partial Pressure.** Partial pressure of a gas equals the fraction (percentage) of that gas times total pressure, or  $PO_2 = FO_2 \times ATA$ , Table 1.1.

Table 1.1. Fraction of gas times total pressure = partial pressure.

| Percentage<br>(fraction) O <sub>2</sub> | Depth<br>(feet meters)        | Pressure<br>(ATA or atm abs) | FO <sub>2</sub> x ATA = PO <sub>2</sub> |
|---|-------------------------------|------------------------------|---|
| 21% oxygen<br>(air)                     | Surface                       | 1                            | 0.21 x 1 = 0.21                         |
|   | 33 10                         | 2                            | 0.21 x 2 = 0.42                         |
|   | 66 20                         | 3                            | 0.21 x 3 = 0.63                         |
|   | 99 30                         | 4                            | 0.21 x 4 = 0.84                         |
|   | 132 40                        | 5                            | 0.21 x 5 = 1.05                         |
|   | 32% oxygen<br>(NOAA Nitrox I) | Surface                      | 1                                       |
| 33 10                                   |                               | 2                            | 0.32 x 2 = 0.64                         |
| 66 20                                   |                               | 3                            | 0.32 x 3 = 0.96                         |
| 99 30                                   |                               | 4                            | 0.32 x 4 = 1.28                         |
| 132 40                                  |                               | 5                            | 0.32 x 5 = 1.60                         |
| 100% oxygen                             |                               | Surface                      | 1                                       |
|   | 33 10                         | 2                            | 1.00 x 2 = 2.0                          |
|   | 66 20                         | 3                            | 1.00 x 3 = 3.0                          |
|   | 99 30                         | 4                            | 1.00 x 4 = 4.0                          |
|   | 132 40                        | 5                            | 1.00 x 5 = 5.0                          |

**Why You Use Partial Pressures.** Partial pressure calculations let you know how much nitrogen and other inert gases you uptake and offgas. How this is done is covered next in Nitrogen Tension.

Mixtures with high oxygen partial pressure are sometimes breathed on decompression stops to shorten decompression stop time after long, deep dives. Reducing PN<sub>2</sub> in the mix by increasing PO<sub>2</sub> promotes nitrogen elimination, while total gas pressure outside the body is kept high enough to resist bubble formation, by the sum of the nitrogen and oxygen partial pressures.

Just as raising PN<sub>2</sub> increases nitrogen uptake, raising PO<sub>2</sub> can increase oxygen uptake. Too much causes toxicity, discussed in Chapter 5; knowing partial pressure calculations for oxygen helps prevent it.

## NITROGEN TENSION

*Nitrogen Tension – Partial pressure of nitrogen in the body.*

Partial pressure of nitrogen in the mix you breathe is usually just called nitrogen partial pressure. Partial pressure of nitrogen dissolved in your body is commonly called nitrogen tension. In other words, ambient nitrogen partial pressure determines compartment tensions. Division of these terms is not standardized. You may also hear the term gas loading.

**Units of Nitrogen Tension.** Nitrogen tensions are partial pressures, so use partial pressure units, often feet of sea water (fsw). Haldane defined sea level pressure in fsw. Much of his and his followers' math use 33 fsw as sea level pressure, so a depth of 33 feet has a pressure of 66 fsw. You may also see meters of sea water (msw), mmHg, torr, bar, atmospheres (atm), and atmospheres absolute (ATA or atm abs), which is air plus water pressure together (see previous section – Units of Partial Pressure). Scientific writing uses International System (SI) units of pascals (Pa) and kilopascals (kPa). All are units of pressure. Don't confuse the units of pressure; fsw and msw, with the units of distance; feet and meters. It's not as difficult as it sounds. A conversion table of common units appears in the Appendix. English and SI systems are explained in the glossary. Also see the glossary for more on the important distinctions between atm, ATA, and technical ATA.

The point is just to understand that nitrogen tensions in your body are pressures, not volumes of gas as sometimes thought, and that you may see the result of many dive computer calculations of nitrogen tension in fsw, a common pressure unit.

**Starting Nitrogen Tension On Land.** The weight of the air column at sea level makes air pressure equivalent to the pressure of 33 fsw, even though you are at zero elevation. Nitrogen partial pressure is the fraction of gas times total pressure, so nitrogen partial pressure is  $0.79 \times 33$ , or 26.07 fsw.

Nitrogen tensions in your body vary from this because the air you breathe in gets "diluted" by water vapor and carbon dioxide from your body. Subtracting water vapor pressure and arterial  $\text{CO}_2$  values gives the blood tension. Tensions in your various compartments will eventually match, or equilibrate with inert gas tension in your blood.

This, more or less, is the compartment nitrogen tension you start with. If you go up in an airplane or to the mountains, your internal nitrogen tensions will all gradually decrease, as there is less ambient pressure, and less nitrogen partial pressure to drive nitrogen uptake. When you go diving, tensions rise from your starting point, because of increased pressure underwater.

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Nitrogen fraction is 79%. Total pressure at sea level is 33 fsw.  
Partial pressure of nitrogen (inspired) is:

$$0.79 \times 33 \text{ fsw} = \text{approx. } 26 \text{ fsw}$$


---

**Nitrogen Tension Underwater.** At 33 feet down, for example, nitrogen partial pressure would be around 52 fsw. How is that number determined? Total pressure at 33 feet of depth is 66 fsw (33 ocean plus 33 for the atmosphere). Partial pressure is percentage times pressure, or  $0.79 \times 66 = 52.14$  fsw.

All your compartment tensions will eventually reach (equilibrate with) external pressure, more or less, given general conditions, individual physiology, and subtracting out water vapor and carbon dioxide pressures. These numbers are not exact in the body, so don't worry about the decimal places. Calculations are often done with inspired gases. Pulmonary gases are not ignored, just sort of held constant, so many models do not consider them separately.

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Nitrogen fraction is 79%. Total pressure at 33 feet is 66 fsw.  
Partial pressure of nitrogen (inspired) is:

$$0.79 \times 66 \text{ fsw} = \text{approx. } 52 \text{ fsw} \quad \checkmark$$

---

Deeper depth increases pressure to drive nitrogen ongassing, increasing compartment nitrogen tensions. Longer bottom time increases tensions. Longer surface intervals decrease tensions. Conservatism with these variables reduces your compartment nitrogen tensions.

**Compartments Reach Different Tensions.** When you dive, you suddenly increase ambient nitrogen partial pressure. However, it takes time to ongas enough nitrogen so that internal  $N_2$  tensions equilibrate with external  $N_2$  partial pressure. Each compartment takes up gas at different rates, meaning each will have a different nitrogen tension after the same period of time. Not all will have enough time to ongas all they can and arrive at equilibrium with ambient pressure. Faster compartments equilibrate, or come close to it, on an average recreational dive. Slower ones remain relatively low. Mid-speed compartments have mid-range nitrogen tensions. Information about half-times allows decompression tables and computers to calculate nitrogen tensions in each compartment at each point in time during your dive.

## HALF-TIMES

*In decompression equations, half-times describe the rate of nitrogen or other inert gas transit into and out of the body.*

✓ A 5 minute half-time compartment fills with inert gas to half the maximum it can hold in 5 minutes. A 10 minute compartment half fills in 10 minutes, a 20 minute compartment half fills in 20 minutes, and so on.

**Half-time Gas Uptake.** At sea level before your dive, compartment tensions are all equilibrated with sea level pressure, described earlier in Nitrogen Tension. Pressure at depth drives more gas uptake, and compartment tensions will become equal to the new pressure after enough time. Compartments get halfway to that new equilibration point, or half 'full' after one half-time. After the next half-time, the remaining half fills by half. The quarter that's left will then fill by 50%, then the remaining eighth, and so on.

Figure 1.3 shows compartments reach 50% of capacity (equilibrium) after one half-time, 75% after two half-times, 87.5% after three half-times, 93.75% after four half-times, and 96.87% after five half-times. By convention, after six half-times, compartments are considered completely equilibrated with the pressure at depth, or "full," explained later in Saturation. ✓

**Gas Elimination:** The Haldane model figures offgassing at the same half-time rate as ongassing, although several factors can slow nitrogen release from your body. Each compartment loses half the remaining amount with each passing half-time, until they all eventually reach equilibrium with sea level pressure again. Faster compartments do this faster than slower ones, Figure 1.4.

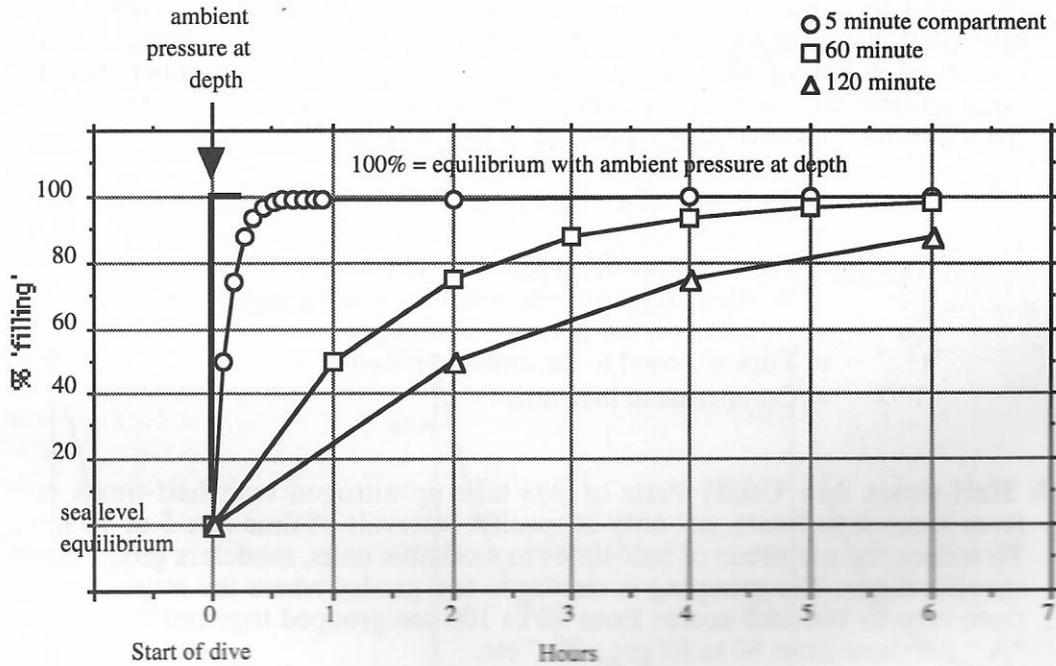


Figure 1.3. Ongassing in the 5, 60, and 120 minute compartments over a six hour dive to any depth. All reach 50% after one half-time: 5 minutes in the 5 minute compartment, 60 minutes (1 hour) in the 60 minute compartment, and 120 minutes (2 hours) in the 120 minute compartment.

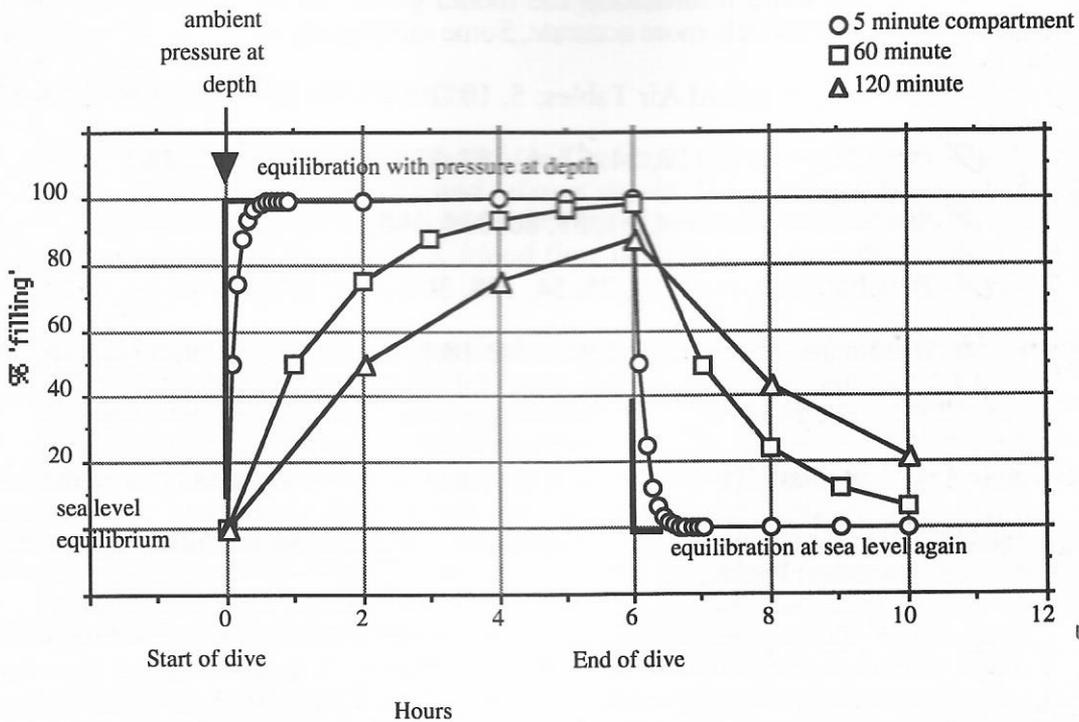


Figure 1.4. Inert gas elimination in the 5, 60, and 120 minute compartments, after first ongassing for 6 hours. All lose 50% of what they started with after one half-time. Slow compartments are slower to gain and lose inert gas, and therefore slower to become equal with surrounding pressure.

**The Half-time Equation.** Tensions in each compartment, at each part of your dive, are estimated using the exponential equation for half-time rate of change (exponents explained in Parts I, II, and the glossary). Then you plug in numbers for starting compartment tensions, inert gas partial pressures at your depth, and time exposed (plus or minus various other factors up to the modeler).

$$P_t = P_0 + (P_a - P_0) (1 - e^{-0.693t / T^{1/2}}) \pm \text{stuff}$$

- P<sub>t</sub> = Total compartment pressure (tension)
- P<sub>0</sub> = Starting compartment pressure (P sub-zero)
- P<sub>a</sub> = Ambient partial pressure of nitrogen
- t = Time exposed to the ambient pressure
- T<sup>1/2</sup> = Compartment half-time

**Which Half-times Are Used?** Parts of you take up nitrogen with half-times ranging from seconds to hours, not only at specific intervals of time like 5 or 10 minutes. To reduce the multitude of half-times to workable units, modelers group them into specific times. The grouping is similar to test grades where the scores may range from zero to 100. All scores from 90 to 100 are grouped together to be called an "A." All those from 80 to 89 get a "B," etc.

Some decompression tables and computers use variations on a standard group of half-time compartments: the 5 minute half-time, the 10 minute, 20 minute, 30, 40, 60, 80, 90, 120, and 240. Others use completely different half-times. How many and which ones are up to the modeler. The more half-time compartments considered, the more information the model gives. More compartments do not necessarily make models more accurate. Some samples follow:

US Navy Standard Air Tables: 5, 10, 20, 40, 80, 120

✓ Orca Edge: 5, 11, 17, 24, 37, 61, 87, 125, 197, 271, 392, 480

✓ Dacor Micro Brain: 4, 11, 31, 86, 238, 396

✓ Beuchat Aladdin: 4, 12, 26, 54, 108, 304

✓ Bühlmann ZHL-12: 4, 7.94, 12.2, 18.5, 26.5, 37, 53, 79, 114, 146, 185, 238, 304, 397, 503, 635

ZH-L<sub>12</sub> !  
 τ<sub>1</sub> = 2.65 min

missy: (160, 200, 240)

**Half-times Are Not Just Theoretical.** A frequent question by divers is if the half-times used in decompression are only theoretical, or if they are an actual phenomenon that occurs in real life. Half-times describe the rate of change of many natural processes, Figure 1.5.

Radiation is one example of a natural phenomenon that behaves according to half-times, although for radiation we call it a half-life. A half-life is the time for a radioactive sample to decay to half its original value. Drug metabolism also behaves according to half-times. Your body takes predictable units of time to eliminate one-half of a standard dose of substances like Valium, other drugs, or carbon monoxide, to name only a few. In pharmacology it's common to call this unit time either a half-time or a biologic half-life. Valium, for instance, has a half-life of

about 24 hours to clear from your body. In one day, half will be gone. Drugs with short half-lives of 1.5 to 3 hours like penicillin must be taken several times a day to keep them from falling below therapeutic level. The local anesthetic Novocain is chosen for dental work for its half-time – long enough to last until completion of dental work, but short enough to eliminate soon after.

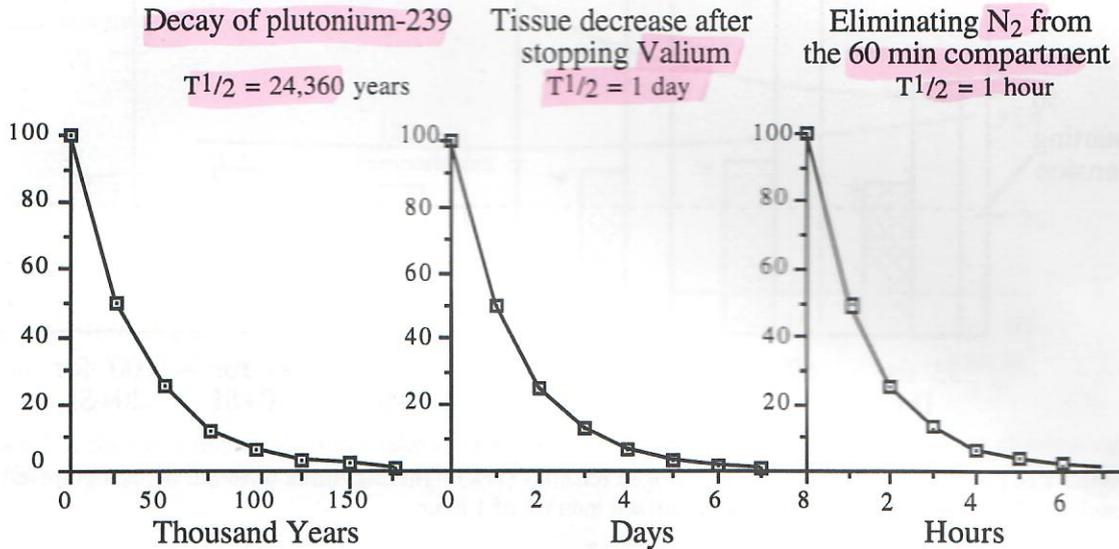


Figure 1.5. Half-time behavior is common in nature.

## FAST AND SLOW COMPARTMENTS

*Fast compartments absorb and release inert gas quickly. Slow compartments absorb and release slowly. In anatomic tissues, rate depends on blood flow and solubility of gas in that area. In Haldane decompression models, blood flow is the main factor establishing compartment speed.*

During most dives, nitrogen tensions become higher in fast compartments than in slow ones, because they take up more gas in the same amount of time. When compartments eliminate gas during surface intervals, faster compartments quickly return to starting pressure. Slower compartments are not much affected by stops or short surface intervals, because they offgas too slowly, Figure 1.6.

**Which is Which?** Confusion sometimes occurs when divers ask which anatomic tissue corresponds to which half-time compartment. Exact half-times are not known for anatomic structures in your body. Experiments and educated “guesstimation” generalize about which body areas are faster or slower.

Body areas well supplied by blood, such as lungs and abdominal organs, absorb nitrogen quickly. Slower tissues are usually considered to include bone, because of low blood supply, and fat and fatty bone marrow. Fat and fatty tissues are slow tissues, but not necessarily for lack of blood supply.

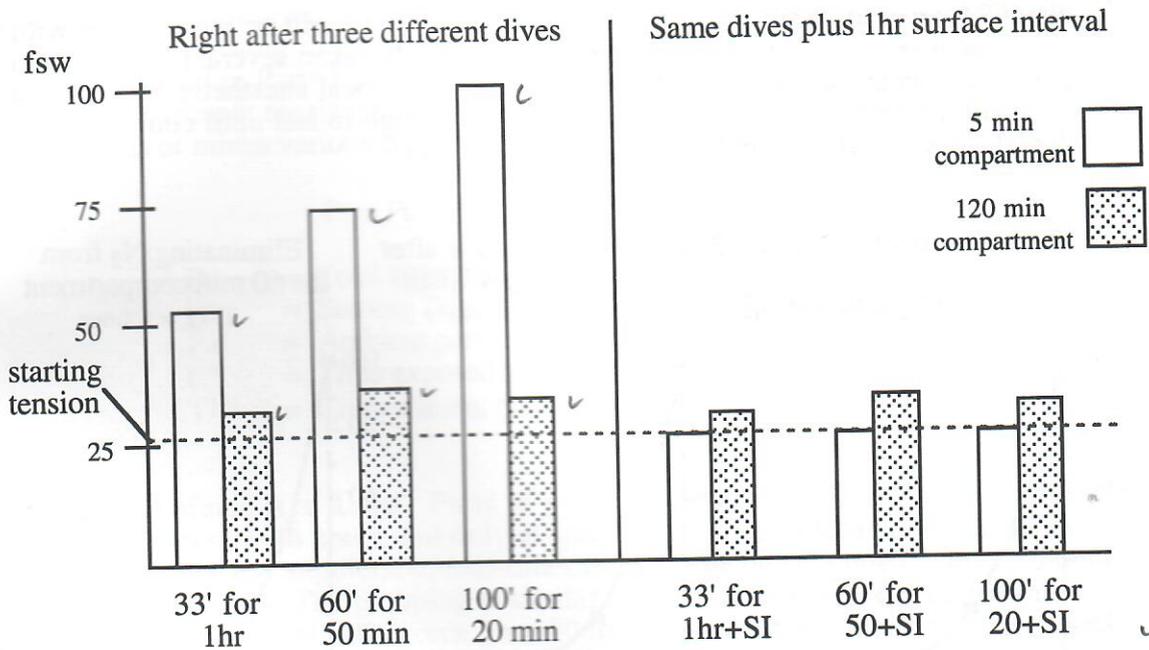


Figure 1.6. Fast and slow compartment nitrogen tensions (fsw) right after three different dives, compared to tensions after the same three dives plus a surface interval of 1 hour.

Nitrogen is more soluble in fatty than watery tissues. It takes longer for nitrogen to fill and leave fatty tissue. This is a property of fat, and true even for fatty areas with similar blood supply as leaner tissue. **Very slow tissues are thought to be avascular areas like cartilage and certain joint structures including the joint fluid called synovial fluid.**

Many body structures are made of several different anatomic tissues, with different properties. The heart, for example, probably has several different areas that take up and give off gas at all different rates. It does not matter to the decompression equations which anatomic tissue is what speed compartment. Decompression compartments cover, or attempt to cover, the spectrum of possibilities in gas exchange.

**Do You Only Offgas On Ascent?** Divers often ask if all your compartments outgas on ascent or “safety stops” because ambient pressure is lower than during the dive. That’s not the case for all compartments.

Slow compartments can take up gas during ascent, at the same time that faster compartments are getting rid of theirs. Slower compartments can still have lower pressures than the surroundings, because they don’t have time during typical recreational dives to become equal to ambient pressure. During ascent, pressure drives nitrogen in the air you breathe into any compartments with lower than ambient pressure. At the same time, fast compartments with higher tensions offgas. Gas can go in both directions, Figure 1.7.

The utility of safety stops is to quickly lower tensions in the faster compartments. Remember that these numbers cannot exactly describe what happens in the body. They show, in general, which tensions would go higher, which lower.

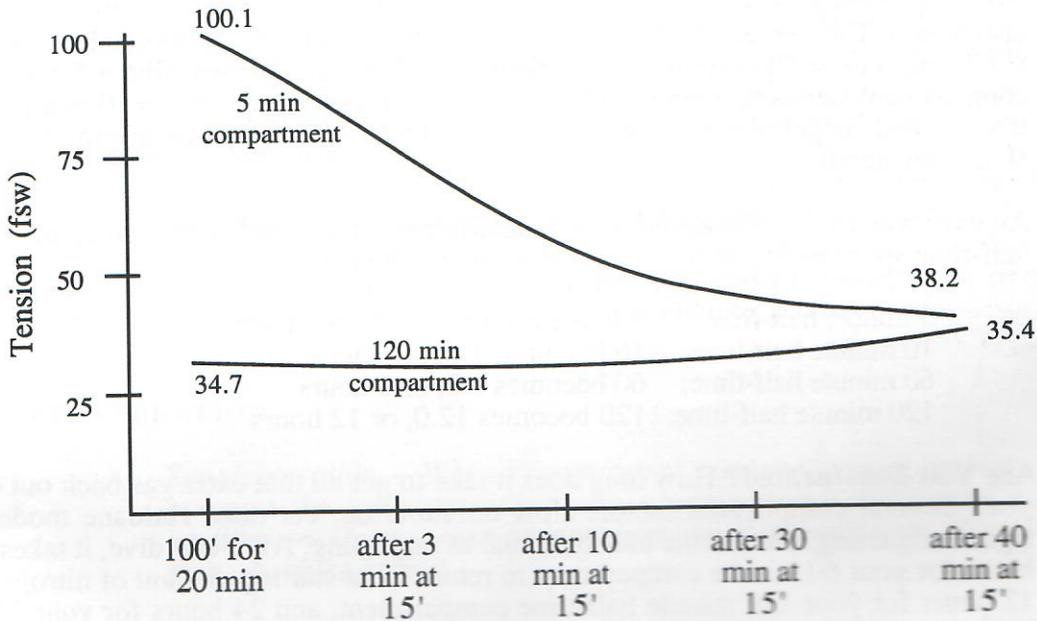


Figure 1.7. Slower compartments can take gas on at the same time that fast compartments are eliminating gas on a stop or when spending time in the shallows after a deeper dive.

### SATURATION AND DESATURATION

*Saturation – When the body contains all the nitrogen or other inert gas it can hold at a given pressure (depth). Occurs when compartments have enough time to become equal with inspired inert gas partial pressure.*

You are saturated with nitrogen right now on land. Your body has all the nitrogen it can hold at the elevation where you live because of air pressure around you. In other words, you are equilibrated with ambient pressure.

The amount of dissolved gas compartments can hold changes with pressure. That is Henry's Law. If you go one foot underwater, increased pressure drives more nitrogen uptake. After sufficient time, your tensions will be the same as the ambient pressure at 1 fsw, and compartments are saturated. If you descend any deeper, you will absorb more nitrogen. After time, you equilibrate with ambient pressure, and are saturated at the new depth.

---

A typical one hour no-stop recreational dive would saturate only your fastest compartments – those with half-times of 10 minutes or less.

---

$$\frac{60'}{6} = 10'$$

**When Are You Saturated?** Divers often ask how long it would take to completely saturate your whole body during a dive. Compartments are 98.44% saturated or desaturated after six half-times. For practical purposes, almost 99% is considered close enough. No matter what the depth, the 60 minute (one hour) compartment

would be considered saturated in 6 hours (6 half-times  $\times$  60 minutes = 360 minutes or 6 hours). The slower 120 minute compartment would take 12 hours (6 half-times  $\times$  120 minutes = 720 minutes or 12 hours). A fast compartment like a 5 minute compartment saturates in only 30 minutes (6 half-times  $\times$  5 minutes = 30 minutes). If you dived deeper, it would take another 6 half-times for compartments to saturate at the new depth.



An easy way to figure saturation (or desaturation) for any half-time is to divide the half-time speed by ten, then change the answer to hours:

|                       |                                  |
|-----------------------|----------------------------------|
| 5 minute half-time:   | 5 becomes 0.5, or 0.5 (1/2) hour |
| 10 minute half-time:  | 10 becomes 1.0, or 1 hour        |
| 60 minute half-time:  | 60 becomes 6.0, or 6 hours       |
| 120 minute half-time: | 120 becomes 12.0, or 12 hours    |

**When Are You Desaturated?** How long does it take to get all that extra gas back out of you? Several complicated factors slow desaturation, but most Haldane models figure offgassing at the same half-time rate as ongassing. After any dive, it takes 6 hours for your 60 minute compartment to return to its starting amount of nitrogen, 12 hours for your 120 minute half-time compartment, and 24 hours for your 240 minute compartment. This is true no matter how short the dive, because whatever amount of gas compartments start with, it takes six half-times to get rid of it. Certain non-Haldane models, discussed in Part III of this chapter, allow more time for desaturation.

**Determined by the Longest Half-time.** The longest compartment considered by the U.S. Navy (USN) Standard Air Decompression Tables, and tables based on them such as the Jeppesen, NAUI, Nu-Way, NASDS, and Dacor, is the 120 minute compartment. It takes 12 hours for the 120 minute compartment to be considered desaturated, and all faster compartments will desaturate more quickly. That's why there's a 12 hour minimum between dives to end the repetitive dive category, and be considered as starting a new dive when using these tables. The DSAT Recreational Dive Planner uses 6 hours as the minimum between dives, and is limited to no-stop diving. It is a variation on the USN-based tables. It takes 24 hours to desaturate the 240 minute (4 hour) half-time. Dives within 24 hours of a previous dive are calculated as repetitive dives. Several dive computers use half-times up to 480 minutes. The 480 compartment takes 48 hours to desaturate. Some models use still longer half-time compartments.

no!  
 120 min  
 for SI

## SATURATION DIVING

*Saturation Diving – Alternative method to repeated decompression after repeated underwater work bouts. Divers remain underwater, working, living, and sleeping, using dry bells and habitats for periods of days, weeks, or longer, becoming saturated with nitrogen or other inert gas in the breathing mixture. Decompression time is the same regardless of length of stay.*

With long, deep diving, nitrogen tensions rise too high to surface without decompression trouble. You must make a stop before surfacing, in some cases several stops at several depths, to lower nitrogen tensions below a critical amount, explained below in the section on M-values. The stops are called decompression stops.

Some commercial, military, and scientific applications require long underwater stays. Long exposures require long decompression stops. Length of the decompression stops often exceeds length of the bottom time. Rather than decompress after each task, science, military, and commercial divers can remain under pressure for the duration of their work. Scientists may live in dry habitats underwater, venturing out to work. Commercial saturation divers can stay in a pressure chamber and “commute” to work underwater in a pressurized bell. In both cases, they remain under pressure and become saturated. Once saturated, they don’t absorb more nitrogen, no matter how much longer they remain at that depth. Decompression stop time is the same if they stay under pressure a day or a week. Saturation diving requires extensive support operations and equipment. ✓

## SUPERSATURATION

*Supersaturation – When compartment tensions exceed ambient pressure, the compartment has more nitrogen than it can contain in equilibrium. Occurs when ambient pressure drops on ascent. Past a point, bubbles form.*

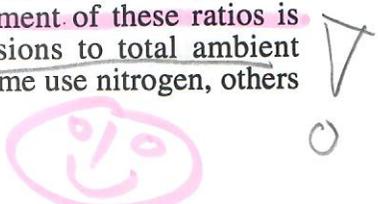
On ascent, ambient pressure drops. Ambient pressure may become lower than nitrogen tensions that have built up in certain compartments (but not all). These compartments will then have more nitrogen than they can contain in equilibrium. Whether that’s dangerous depends on how much supersaturation exists for how long. Past a point bubbles form. That point is called critical supersaturation. Some researchers believe bubbles are probable after any degree of supersaturation.

Fast ascents may allow too much nitrogen to come out of solution too fast, forming bubbles and decompression problems. One decompression accident report quoted a diver who stated he ascended rapidly to meet a no-decompression time limit, thinking it would reduce his risk of DCS. Such accelerated ascent may increase risk of a decompression problem. It’s better to make a slower ascent with slightly more total time.

## SUPERSATURATION RATIOS

*Supersaturation Ratio – Compartment nitrogen tension at depth compared to (divided by) total pressure at the surface or decompression stop. Exceeding the supersaturation ratio produces bubbles or likelihood of bubbles. Each half-time compartment has a different supersaturation ratio.*

Haldane did not distinguish between the point where bubbles form and decompression sickness. His work was symptom based. He found that direct ascent to the surface (one atmosphere absolute) was possible from unlimited time at two atmospheres absolute, or to two from four, without decompression symptoms. He assumed the tolerance to pressure halving held for all compartments. His decompression tables limited supersaturation ratios in all compartments to two. This is now called a 2:1 supersaturation ratio. Today we believe that fast compartments tolerate higher supersaturation ratios than slow compartments before bubbles become a problem. The literature on the whole development of these ratios is confusing. Some look at ratio of internal nitrogen tensions to total ambient pressure, others to ambient partial pressure of nitrogen. Some use nitrogen, others



use air. Each arrives at different numbers. We also now know that bubbles often form with no symptoms. M-values, covered next, take the supersaturation concept further and try to define when your compartments have had enough.

Divers aren't the only ones who have to know about supersaturation ratios. When you ascend from land to altitude, ambient pressure drops. Pressure does not drop as much per distance as underwater, because air is lighter than water. You have to go to 18,000 feet before pressure drops to half that of sea level. That's a good thing – you wouldn't want to get decompression sickness every time you took a fast elevator. There have been cases of decompression sickness in flight crews who experienced large, rapid cabin depressurization during a flight emergency (as well as air embolism and ear equalization trauma). Decompression sickness is also a concern in extravehicular travel during space flight. The space shuttle is kept at one atmosphere absolute of regular air. The pressure inside space suits is less than one atmosphere absolute. To get into the suits, astronauts first breathe oxygen to outgas nitrogen.

## M-VALUES

*M-values – Maximum nitrogen (or other inert gas) tensions that various compartments are thought to tolerate before supersaturation produces a harmful amount of bubbles.*

The 2:1 supersaturation ratio for all compartments worked well for the applications for which they were developed, but did not prevent problems as well in other exposures. The US Navy began work to modify the Haldane tables. By the late 1950's, R.D. Workman of the US Naval Experimental Diving Unit (NEDU) systematized work done by others and experimentally determined maximum nitrogen tensions in different compartments before bubbles are thought to form. These maximum tensions are called M-values. (M is for maximum). M-values exist for any inert gas used. M-values in this chapter refer to nitrogen, unless noted.

Decompression tables and computers limit depth and time so no compartment exceeds its M-value at any point during the dive. This is accepted to reduce decompression problems. Bubbles have been found in recreational divers after profiles that don't exceed established limits. M-values are not magic limits that prevent bubbles. Avoid diving the time and depth limits of your tables or computer. The numbers can only approximate what is happening.

**M-Value Units.** M-values are pressures, so units are pressure units. The unit fsw is used, as it is convenient to have M-values in the same units as the dive for easy comparison.

**Different M-Values for Different Compartments.** Fast compartments tolerate higher supersaturation ratios than slow compartments, so have higher M-values. According to the US Navy Standard Air Decompression Tables for example, a five minute compartment was empirically observed to tolerate a maximum nitrogen tension at the surface of 104 fsw, a 120 minute compartment, only 52 fsw.

Table 1.2 compares half-time compartments and their corresponding M-values in two models. For perspective, remember that all your compartments start with a nitrogen tension approximately 26 fsw at sea level (79% of 33 fsw).

Table 1.2. Comparison of M-values (fsw) in two different models, the US Navy Standard Air Decompression Tables, and the DSAT RDP. In both, fast compartments are considered to tolerate higher supersaturation ratios than slow tissues, so have higher M-values.

|         | Half-time ( $T^{1/2}$ ) |       |       |       |       |    |       |       |       |
|---------|-------------------------|-------|-------|-------|-------|----|-------|-------|-------|
|         | 5                       | 10    | 20    | 30    | 40    | 50 | 60    | 80    | 120   |
| US Navy | 104                     | 88    | 72    | -     | 56    | -  | -     | 54    | 52    |
| DSAT    | 99.08                   | 82.68 | 66.89 | 59.74 | 55.73 | -  | 51.44 | 49.21 | 46.93 |

**Different M-Values for Different Depths.** Each compartment has different M-values for different depths.

Recreational no-stop diving is based on being able to ascend directly to the surface. Your decompression table or computer tells you to surface before any of your compartments reach M-values allowed at the surface. Surface M-values are written  $M_0$ , pronounced M sub zero. If compartments would exceed  $M_0$ , you make a decompression stop to let your compartments drain down until they are below  $M_0$ .

$M_{10}$  is the maximum tension you can build up and get to within 10 feet of the surface, with acceptable risk. If you have built such high nitrogen tensions that you should not ascend as far as the decompression stop at 10 feet, you do a deeper stop to offgas enough to ascend further.

**Controlling Compartments.** M-Values allow decompression tables and computers to determine depth and time limits for different compartments, then base the limit for the entire body on the compartment that would first reach its maximum. That compartment is called the controlling compartment.

## TABLE-BASED AND MODEL-BASED COMPUTERS

*Table-Based Computer* – Looks up the dive profile against values already determined by a decompression table.

*Model-Based Computers* – Calculates decompression for the actual depth-time profile in real time.

The many Haldane based decompression computers give their final answer in two ways. A very few look up the dive profile against values that have already been determined by a decompression table. They assign the actual dive profile to a predetermined depth-time profile that is closest. These are called Look-Up or Table-Based Computers. The majority of computers are Model-Based – programmed with the decompression calculation algorithm. They calculate decompression for the actual depth time profile.

RDP  
160  
- 480  
Missing

## CHAPTER 1 PART IV

### INTRODUCTION TO NON-HALDANE MODELS

---

Some decompression models view gas transport or bubble formation different from the Haldane model. Their development grew from need to reduce decompression problems in dive profiles not covered by the Haldane model, and because several issues in decompression dynamics remain unexplained by existing decompression theory. As mentioned in Part II, the tables are not just number fiddling, but based and adjusted from experience. Concepts behind a few of several non-Haldane models are briefly summarized.

- Statistical Models
  - Series Model
  - EL Model
  - Varying Permeability Model
  - Reduced Gradient Bubble Model
  - Slab Model
- 

#### STATISTICAL MODELS

*Statistical Model – Decompression tables that approach decompression statistically; out of so many dives of a specific type, so many DCS incidents are expected.*

Some decompression models approach decompression statistically, that out of a given number of dives of a specific type, a certain number of DCS incidents is expected. The US Naval Medical Research Institute (NMRI) in Bethesda developed several statistical tables using maximum likelihood calculations developed by Dr. Paul Weathersby.

One table for air diving gives dive profiles with 1% risk of decompression sickness. A second table for air diving has longer profiles with 5% predicted risk. Which profile is chosen depends on priority and length of the dive mission. Other tables use gases other than nitrogen, also profiling dives with 1% or 5% risk. According to decompression physiologist Dr. Bill Hamilton, statistical models are the coming wave in decompression models.

## SERIES MODEL

*Series Model – Decompression model where inert gas is assumed to pass serially from compartment to compartment. Only one compartment is considered exposed to the ambient pressure reached in the blood stream. The Canadian DCIEM tables are calculated with a series model. Also called serial model*

In 1962, researchers D.J. Kidd, a Canadian Navy surgeon, and R.A. Stubbs, a Canadian Air Force scientist, began work to develop a dive computer. They started with a Haldane parallel model and later decided that a series (serial) model better represented the human body.

Decompression tables and computers based on the Haldane model assume that compartments on gas and off gas separately but at the same time directly to and from your blood. The idea of separate, simultaneous, gas transfer is called parallel gas transfer. In a parallel model, no gas transfer is assumed between compartments, Figure 1.9.

It's unlikely that all gas diffuses to and from compartments in parallel. Adjacent compartments are often of different half-times. Higher nitrogen pressure areas reside next to lower pressure areas. Nitrogen would flow from higher to lower pressure areas. Gas transit from compartment to compartment is called series transfer. Only one compartment is considered to be exposed to the ambient pressure reached in the blood stream, Figure 1.10. The phenomenon of serial transfer has been observed in pharmaceuticals. A series model may account for nitrogen transfer as well. According to decompression modeler Dr. Hugh Van Liew of SUNY Buffalo, "Both kinds of model attempt to describe reality. Reality may be more complex than either model."

The first Kidd-Stubbs "computers" were built before microprocessors. Their first model, simulating a parallel model, was made of pipes of different lengths connected with small orifices to simulate gas diffusion into the compartments. The short pipes were fast half-time tissues because they filled quickly. The long pipes were slow tissues, taking longer to fill. A pressure gauge on each pipe showed the pressure within each "compartment." These computers were called pneumatic because the only driving force required was the gas pressure. Their series model took several different forms in the prototypes. Later versions were machined compartments of the same volume connected up by "pneumatic resistors" controlling rate of flow into and out of the compartments.

The two laboratories where Kidd and Stubbs worked (Canadian Forces Institute of Environmental Medicine and the Defence Research Medical Laboratory) merged in 1971 to form DCIEM – the Defence and Civil Institute of Environmental Medicine in Canada. The Kidd-Stubbs computers, first the pneumatic-mechanical, and later, pneumatic-electronic devices were used for much of the experimental diving at DCIEM in the 1970's. As microprocessor and digital technology replaced pneumatic technology, DCIEM converted to a digital microprocessor-controlled computer using the mathematical algorithm from the Kidd-Stubbs series model.

The present DCIEM Kidd-Stubbs tables were developed by the DCIEM group led by Ron Nishi. They use four compartments in a series. These compartments don't have set half-times. Compartments on gas and off gas to each other. Different filling times result for each, depending on depth and conditions.

no!  $\tau_{1/2} \approx 2.1$

### Parallel Gas Transfer

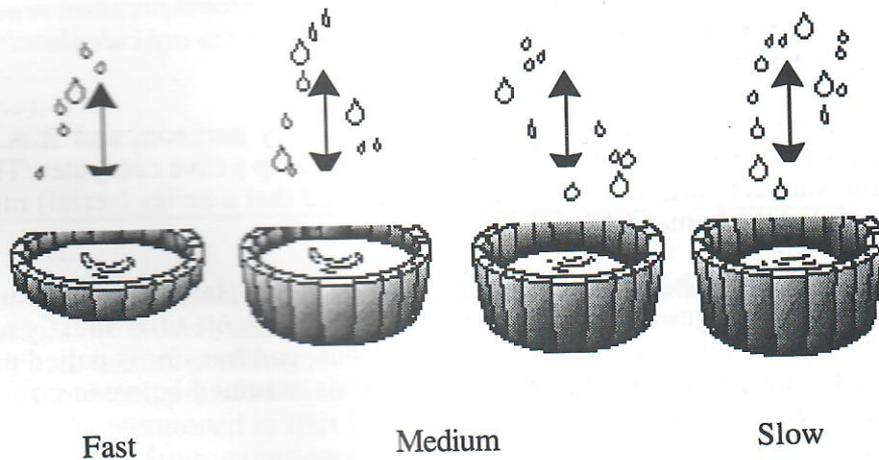


Figure 1.9. Compartments are considered to be exposed separately to ambient pressure from the blood, and ongas and offgas separately to and from your blood. No gas transfer is assumed between compartments. Haldane models assume parallel gas transit.

### Series Gas Transfer

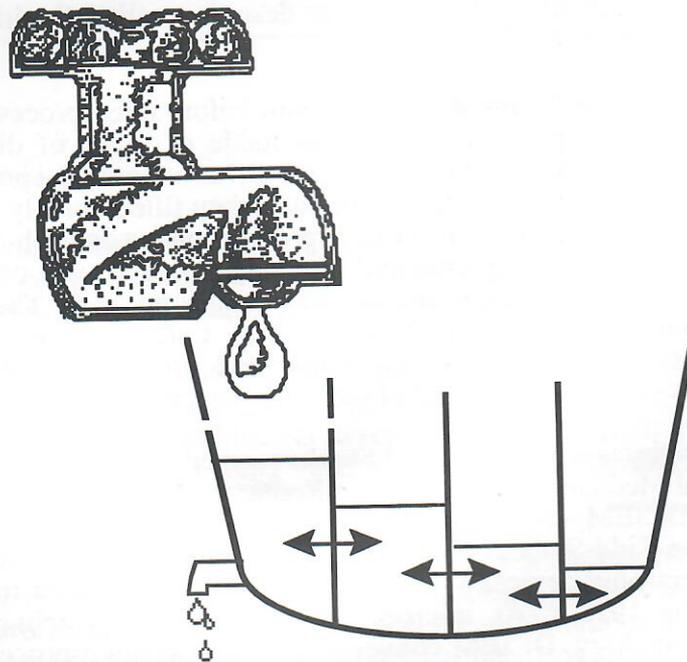


Figure 1.10. Only one compartment is assumed to be exposed to the ambient pressure reached in the blood. Compartments do not have set half-times, and ongas and offgas to each other.

⚡

↑ they do have!  
 $\tau \approx 2\alpha$

## EL MODEL

*EL Model – Decompression model where inert gas uptake is calculated as exponential (E), and offgassing as linear (L).*

EL stands for Exponential and Linear. The EL model is a variation of the Haldane model. The EL is a parallel model that describes on-gassing at exponential rate, as in Haldane models, but as soon as supersaturation occurs, a slower linear off-gassing is used, Figure 1.8 (Part III explains these terms). Haldane decompression models calculate on-gassing and off-gassing at the same exponential rate. Linear off-gassing requires longer stays during decompression stops.

The Haldane model assumes no bubble formation on ascent, however it does occur, and when bubbles occur, they slow off-gassing. Haldane models then cannot accurately predict off-gassing time. This slowed off-gassing may produce more bubbles. Another factor changing off-gassing dynamics is that blood flow normally changes rapidly all over the body. Slower ascent times using the EL model are believed to limit bubble formation.

Capt. Ed Thalmann of the Naval Experimental Diving Unit (NEDU) and his group developed the EL model as a basis for a US Navy diver-carried computer for combat swimmers.

They found that the profiles generated by the exponential off-gassing of the USN tables were not conservative for the depth/time dive profiles they needed.

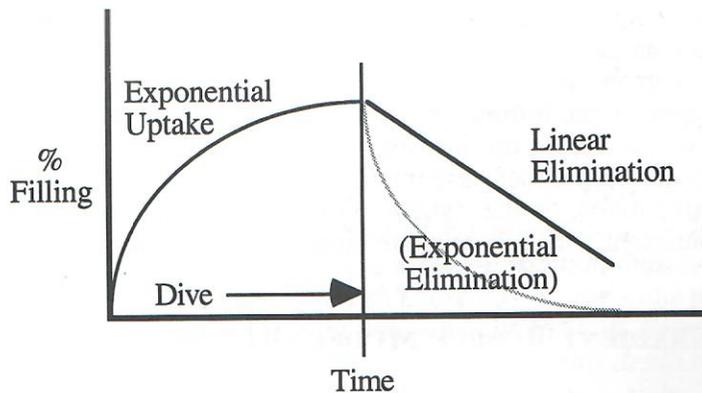


Figure 1.8. Filling and emptying curves for the EL model.

## SLAB MODEL

*The slab model uses one compartment, called a slab, rather than several separate compartments. Gas diffuses through one area of the slab to get to another.*

The slab model describes decompression dynamics in the body using one compartment, called a slab, rather than several separate compartments. Gas diffuses through one area of the slab to get to another.

The fastest area is considered exposed to the ambient pressure of gas in the blood. The slowest, farthest away.

The British Sub-Aqua Club (BSAC) tables use the slab model. They were developed by Dr. Tom R. Hennessy of London.

## VARYING PERMEABILITY MODEL

*Varying Permeability Model – Decompression model limiting bubble size on ascent to a critical volume, and quantity to below a critical number. Also called the Tiny Bubble model.*

Haldane-based tables and computers calculate limits for dives based on eliminating gas that is dissolved in your body, not gas that has come out of solution to form a free gas phase and bubbles. When bubbles form in your body they slow further nitrogen exit by several mechanical and chemical means. To account for free phase bubbles, several bubble models were developed. One is the Varying Permeability Model developed by a group of University of Hawaii researchers led by Drs. Yount and Hoffman. Their work descended from experiments of bubbles in supersaturated gelatin. They believe the size and number of bubbles is important, and that the body can tolerate a certain amount for long periods of time. Their research group is called the Tiny Bubble Group.

They base their model on very small gas phases stable enough to remain bubbles, but small enough to remain in solution. Surface-active molecules on the bubble skin keep them stable. The varying permeability model limits bubble size on ascent to a critical volume, and number to below a critical number, called delta-n, which changes with depth and time. For short decompressions times, bubbles don't have time to grow very large. The model allows many small bubbles. With long decompressions, bubbles have time to get big. The model restricts ascent to only allow a few. Based on this, the model calls for safety stops or shallow swimming, shorter no-stop times, ascent rates not over 60 ft/min, and restrictions on deep repetitive dives, 'spike' (shallow to deep) dives, and multi-day diving. All of these are consistent with conservative table use in general.

## REDUCED GRADIENT BUBBLE MODEL (RGBM)

*Reduced Gradient Bubble Model (RGBM) – Decompression model using reduced surface gradient on repetitive dives.*

Another free phase bubble model is the Reduced Gradient Bubble Model descended from the tiny bubble model described above. It was developed by theoretical physicist Dr. Bruce Wienke, and partly based on the work of Yount and Hoffman. The RGBM reduces the surface gradient on repetitive dives. Surface gradients are much like M-values, where shorter half-times have larger values than longer half-times. Reduced allowable surface gradients shorten no-stop diving time on repetitive dives. The RGBM also tries to account for diving deep after a previous shallow dive, and for multi-level diving.

## CHAPTER 1 PART V

### DIVING WITH GASES OTHER THAN AIR

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Diving with gas mixtures other than regular air is not a new idea. Commercial, scientific, and military applications have long used helium, nitrogen, and oxygen in varying concentrations, and occasionally hydrogen, argon, and neon combinations with oxygen for depth and time exposures not suitable for regular air.

Breathing mixes have high technical, equipment, and training requirements. Get training through mixed gas training organizations before you try it.

- Oxygen Enriched Air
  - Heliox
  - Trimix
  - Gas Switching
- 

#### OXYGEN ENRICHED AIR

*Oxygen Enriched Air (OEA) – Breathing mixtures with higher oxygen percent or fraction and lower nitrogen fraction than regular air. Used to reduce decompression sickness risk on the same profile as an air dive, or to extend bottom time with similar risk. Because of increased oxygen, OEA mixes are not used to extend depth range. Also called Enriched Air Nitrox (EAN).*

The term nitrox historically referred to mixtures with less than 21% oxygen, commonly used in habitats and saturation situations to avoid oxygen toxicity problems. When oxygen percentage is above the normal 21% of regular air it is called enriched air nitrox (EAN or EANx) and/or oxygen enriched air (OEA). All the terms are often interchanged, which is sometimes confusing. Two EAN mixes are currently popular. NOAA Nitrox I, called EAN32, has 32% oxygen and 68% nitrogen. NOAA Nitrox II, or EAN36, is 36% oxygen, 64% nitrogen. ✓

Mixtures with more oxygen and less nitrogen than air incur less nitrogen uptake, compared with air. Compared with air, you can dive longer, or increase your safety margin for the same profile. ✓

0

**Equivalent Air Depth (EAD).** Equivalent Air Depth (EAD) is the depth defined by the partial pressure of nitrogen you breathe, rather than your actual depth. For a mix with less nitrogen than air, EAD is shallower than if you were breathing air. Understanding EAD helps you see how less nitrogen allows you to dive longer or deeper, with nitrogen tensions as if at shallower depths, Table 1.3.

EAD is calculated with a partial pressure equation:

$$\text{EAD (fsw)} = \frac{(1-\text{FO}_2)(\text{D}+33)}{0.79} - 33$$

(1-FO<sub>2</sub>) is the fraction of nitrogen, because FO<sub>2</sub> is the fraction of oxygen, so subtracting it from 1 gives what's left, or nitrogen.

D is your actual depth in feet of sea water (fsw).

(D+33) adds 33 fsw (for the atmosphere) to the measured depth to get absolute depth.

Dividing by 0.79, the fraction of nitrogen in air, gives the equivalent absolute depth.

Subtracting 33 fsw gives the measured depth to use in dive tables.

Table 1.3. Equivalent air depth (EAD) examples. EAD is shallower than actual depth because there is less nitrogen in the mix.

| Breathing Mix                 | Actual Depth (fsw) | Equivalent Air Depth (EAD) with respect to nitrogen (fsw) |
|-------------------------------|--------------------|---|
| Air                           | 80                 | 80  |
| EAN32 with 32% O <sub>2</sub> | 80                 | 64 ✓  |
| EAN32 with 32% O <sub>2</sub> | 100                | 81.5 ✓  |
| EAN36 with 36% O <sub>2</sub> | 80                 | 58.5 ✓  |
| EAN36 with 36% O <sub>2</sub> | 100                | 75 ✓  |

EAN mixes are not used to extend depth range. The higher oxygen content creates risk of oxygen toxicity at shallower depths than air. The maximum operating depth (MOD) for nitrox is shallower than for air. MOD varies with application and work load. Maximum operating depth (varying with conditions) for EAN32 is approximately 130 feet. For EAN36, 110 feet. Oxygen toxicity, and variables affecting maximum operating depth are described in Chapter 5, Diving Injuries. EAN diving requires additional training specifically for nitrox.

Enriched air nitrox diving uses special nitrox decompression tables and computers. Because nitrox tables are currently based on the same Haldane model as many air decompression tables, EAD can also figure the equivalent depth with respect to nitrogen to apply regular air decompression tables to enriched air nitrox dives.

Calculating EAD is a good mental exercise on land, but it is simpler and less prone to calculation error to use tables for nitrox diving where EAD is done for you.

### **Enriched Air Nitrox Misconceptions:**

- A misconception that has made the rounds of divers is that decompression sickness from an enriched air nitrox dive is somehow less serious, or that enriched air nitrox bubbles in the body are less injurious than those from air diving. There is no good evidence that the bubbles or consequences differ in each.
- Breathing enriched air nitrox does not rule out hyperbaric chamber treatment in case of decompression sickness. The increased oxygen would not add appreciably to risk of oxygen toxicity during chamber treatment. Treatment for DCS after diving with EAN is the same as after diving with air.
- Divers often ask if oxygen has mood-elevating qualities. Such questions stem from reports of feeling better after enriched air nitrox diving than air diving, and after oxygen treatment for diving injury. There is good evidence that oxygen does not cause euphoria, but often relieves physical symptoms, which could improve spirits. High nitrogen burden may contribute to fatigue after dives. Extreme fatigue that is due to bubbles is a type of decompression illness. Reducing the nitrogen burden with more oxygen reduces the likelihood of nitrogen related fatigue and feeling unwell. Studies of breathing 100% oxygen before and after exercise at sea level show no physical mood-boosting effects, although a percentage of experimental subjects who were told they were breathing oxygen, but received room air, reported elevated mood. Football players often breathe oxygen believing it will help them, but several studies show oxygen has no beneficial physical effect before, during, or after short, intense efforts such as football. Mood effect of oxygen under hyperbaric pressures is less well studied.

### **HELIOX**

*Heliox – Mixture of helium and oxygen. Helium replaces some or all nitrogen, and part of the oxygen. Reduces or eliminates nitrogen narcosis on deep dives, and allows oxygen level to be controlled to reduce risk of oxygen toxicity.*

Originally only in military, commercial, and scientific diving realms, very deep dives are now done by well-trained, well-equipped, private citizens for fun. These dives often use helium-oxygen mixes, called heliox. Helium replaces part of the oxygen in air, and some or all of the nitrogen. Less oxygen reduces oxygen toxicity. Helium causes less narcosis than nitrogen (some say none), meaning it can be used at depths that would incapacitate a diver with nitrogen narcosis. Helium is easier to breath than nitrogen at depths of hundreds of feet, reducing the work of breathing that would otherwise be a substantial hindrance and health hazard. Helium causes Donald Duck voice. Applications where the diver must communicate with others by speech use helium speech unscramblers. Use of heliox requires special heliox training. ✓

### **Helium Misconceptions:**

- Helium does not necessarily reduce decompression time. Helium does not dissolve as well in your tissues because it is naturally less soluble than nitrogen.

However, the helium that dissolves passes into your tissues faster than nitrogen. Technically speaking, helium is less soluble but more diffusible than nitrogen, making helium half-times over 2½ times faster than nitrogen half-times. According to decompression physiologist Dr. Bill Hamilton, ascent after saturation diving is faster with helium than nitrogen, everything else being the same, but since helium loads faster, decompression may be faster with nitrogen than helium for short exposures. All the variables make it complex.

- It is not the case that Donald Duck voice is due to the vocal folds (cords) vibrating faster in helium than in air. Two main reasons for voice change are speed of sound and impedance match. These two don't account for everything, but do account for most of it. The main consideration is the different speed of sound in different gases. Sound travels faster in low molecular weight gases like helium. The second factor is the shift in low frequency vocal resonances in gases of different density. The shift results in the nasal voice of deep chamber dives, but that is different from Donald Duck voice. The fundamental pitch of vocal fold (cord) vibration doesn't change with density of the breathing gas. Dr. David Doolette of Australia points out that if it did, the Donald Duck voice would gradually lower to normal at depth while breathing helium, and your normal voice would rise to Donald Duck pitch when going to altitude while breathing air.

- There is much discussion whether you get colder breathing helium than breathing air. Helium has greater thermal conductivity than air. Undeniably, you lose more heat when surrounded by helium than by air, because heat conductance is the major factor in skin heat loss. Therefore helium is not used in dry suits. However, respiratory heat loss depends on heat capacity, and not at all on conductance. The thermal capacity of helium per gram is higher than that of air. However, there are fewer grams of helium for the same volume breathed because it is far less dense, making thermal capacity less compared to the same volume of air. Less heat would be lost breathing helium, so it should not chill you to breathe, as commonly thought. In a helmet or full face mask, your face may feel cool, making it hard to separate out the lesser loss through breathing. Depth affects gas density, and so heat loss through the breathing medium, and to be more confusing, you also need to account for interactions of respiratory heat loss through convection and evaporation. With helium you may also be more aware of the cold that is so common in diving, than when dulled by narcosis while breathing non-helium mixes. Remember too, it is generally not feasible to breathe air at depths where helium is used, so hard to compare in actual use. The short answer seems to be that breathing mixtures of helium at depths encountered by technical divers does not result in greater cooling than breathing air. Helium feels colder to your skin than air, but it carries away less heat when you breathe it.

## TRIMIX

*Trimix – Mixture of three gases for diving beyond the air range, usually helium, oxygen, and nitrogen.*

Trimix is a helium-nitrogen-oxygen breathing mix. Helium replaces some of the nitrogen and oxygen to reduce narcosis and oxygen toxicity, as explained above in the section on heliox.

Because helium is expensive, some nitrogen is kept in the mix, popularizing trimix over heliox for many but not all deep pleasure dives. Because of narcosis that may

occur, divers using trimix must consider depth and conditions to determine suitability of nitrox for their dive. These considerations and others are covered in special training that divers need before trying trimix.

Another application for a trimixture is extreme depth diving. At depths past 600 feet or so, pressure begins to exert an excitatory effect on the nervous system called High Pressure Nervous Syndrome (HPNS). Pressure itself seems to cause HPNS, not helium, as sometimes thought. Adding a small amount (5-10%) of nitrogen back into the mix reduces HPNS. Nitrogen is a neural depressant at high pressure. Some consider trimix the choice over heliox for deeper work, but others don't agree.

## GAS SWITCHING

*Gas Switching – Changing the breathing gas during a dive, sometimes several times, to keep gas partial pressures within acceptable ranges and/or assist inert gas elimination. Requires much training and logistics.*

Divers can't breathe the same mix at all depths during deep diving. Divers switch from higher percentage oxygen mixes during descent, to lower percentage "bottom mix" to keep  $PO_2$  within acceptable range. They switch again to higher "travel" mixes during ascent, then sometimes higher mixes again for decompression hangs. Such switching require training, complicated and large equipment set-ups, gas logistics, and special decompression calculations, often custom "cut" by decompression table experts.

**Hypoxic and Normoxic.** Gas mixes like heliox and trimix used at great depth must have a lower oxygen percentage than regular air to reduce risk of oxygen toxicity. Sometimes  $PO_2$  is so low it would not keep you alive if you breathed it on land. That is called a hypoxic mix. At depth, the increased partial pressure provides enough oxygen molecules to support your life.

Consider a hypoxic mix containing only 2% oxygen. It would not keep you alive on land. At 313.5 feet,  $PO_2$  rises to the equivalent of a 21% mixture of air ( $PO_2 = 0.21$  ATA). A 5% oxygen mix, also too low to sustain your life on land, becomes normoxic at 105.6 feet. Normoxic means that the partial pressure approximates that at sea level, 0.21 ATA, regardless of true fraction. Divers doing profiles so deep they require gas switching must plan their equipment to get the right mix for their depth. A bottom mix with low  $O_2$  will suffocate you when shallow. A higher  $O_2$  travel or decompression mix can result in oxygen toxicity if used when deep.

**Decompression Mixes.** Decompression mixes are high oxygen mixes of varying percentages up to 100%. They are used during decompression stops of deep and technical dives to reduce decompression "hang" times and risk of decompression sickness. They are also called intermediate mixes and hang mixes.

High oxygen mixes increase the nitrogen offgassing gradient, to reduce decompression hang times and risk of decompression sickness. They are not for use at depth. Tragedies have occurred when divers mistook their high oxygen mix regulator for the backup regulator at depth, and suffered an oxygen toxicity convulsion.

For any breathing mix other than compressed air, make sure every tank you use is analyzed for oxygen content. Changes in temperature and pressure when filling tanks can change the mix. Oxygen content may not be what you expect. Read about ideal gas behavior in the glossary.

Without training, it is risky to dive with special gas mixtures. Get good training before you try non-air mix diving.

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## CONCLUSION

Oh  
yes!

There is much more to decompression theory than presented here. This chapter will get you started with the basics. Whether you use decompression equations or not, it is helpful to understand the concepts behind them. A good understanding of what is known allows you to make better decisions about decompression tables and computers to dive more safely. You will also be better able to spot misinformation.

The object of all decompression tables and computers is to maximize diving time, minimize physiologic problems of breathing oxygen, nitrogen, and other gases, and do it reliably which means repeatedly with similar results. Decompression tables and computers vary on a continuum of conservative to liberal. No tables or computers are risk free. In decompression theory, as in pharmacology or any other physiologic issue involving dose of a substance and its response, we do not yet have the perfect way to describe nitrogen leaving your body, thereby completely preventing decompression sickness. In decompression theory, more is unknown than known. The models that are the basis for current decompression computers and tables are rough approximations of the complex biologic system that is your body.

Many decompression sickness cases result from improperly using tables and computers. Major considerations in your risk are depth, time, and ascent rate (Chapter 5). You can easily control these, and use your tables and computers conservatively to increase your safety margin. The responsibility to use tables and computers properly is yours.

# APPENDIX

## PRESSURE CONVERSIONS

A few units of pressure used in this text, such as fsw, msw, ATA, psi, and mmHg, are commonly seen in several kinds of diving applications, although the International System of Units (SI) is preferred for scientific use. SI units of pressure are the pascal (Pa = Newton x m<sup>-2</sup>), the kilopascal (kPa), and the megapascal (MPa). The SI and English systems are explained in the glossary, along with the metric system and metric units used in SI.

This table gives conversions and notes from the Standard Practice for Use of the International System of Units (SI). Document E380-89a, American Society for Testing and Materials, Philadelphia, PA, 1989.

|         |                            |          |                             |
|---------|----------------------------|----------|-----------------------------|
| 1 atm = | 1.013247 bar ✓             | 1 torr = | 133.322 Pa <sup>a</sup> ✓   |
| 1 atm = | 1.013247 bar ✓             | 1 atm =  | 33.08 fsw ✓                 |
| 1 atm = | 101.3247 kPa ✓             | 1 bar =  | 32.646 fsw <sup>b,d</sup> ✓ |
| 1 atm = | 14.6959 psi ✓              | 1 fsw =  | 3.063 kPa ✓                 |
| 1 atm = | 760.00 torr <sup>a</sup> ✓ | 1 fsw =  | 22.98 torr ✓                |
| 1 bar = | 100.000 kPa ✓              | 1 psi =  | 2.251 fsw ✓                 |
| 1 bar = | 100,000 kPa ✓              | 1 atm =  | 10.13 msw ✓                 |
| 1 bar = | 14.50377 psi ✓             | 1 bar =  | 10.00 msw ✓                 |
| 1 bar = | 750.064 torr ✓             | 1 msw =  | 10.000 kPa <sup>c,d</sup> ✓ |
| 1 MPa = | 10.000 bar ✓               | 1 msw =  | 1.450 psi ✓                 |
| 1 psi = | 6,894.76 Pa <sup>a</sup> ✓ | 1 msw =  | 75.01 torr ✓                |
| 1 psi = | 51.7151 torr ✓             |          |                             |

<sup>a</sup> Signifies a primary definition, from which other equalities were derived

<sup>b</sup> Primary definition for fsw; assumes a density for seawater of 1.021480 at 4°C (the value often used for depth gauge calibration).

<sup>c</sup> Primary definition for msw; assumes a density for seawater of 1.01972 at 4°C.

<sup>d</sup> These primary definitions for fsw and msw are arbitrary since the pressure below a column for seawater depends on the density of the water, which varies from point to point in the ocean. These two definitions are consistent with each other if a density correction is applied. Units of fsw and msw should not be used to express partial pressures and should not be used when the nature of the subject matter requires precise evaluation of pressure; in these cases, investigators should carefully ascertain how their pressure-measuring devices are calibrated in terms of a reliable standard, and pressures should be reported in pascals, kilopascals, or megapascals.