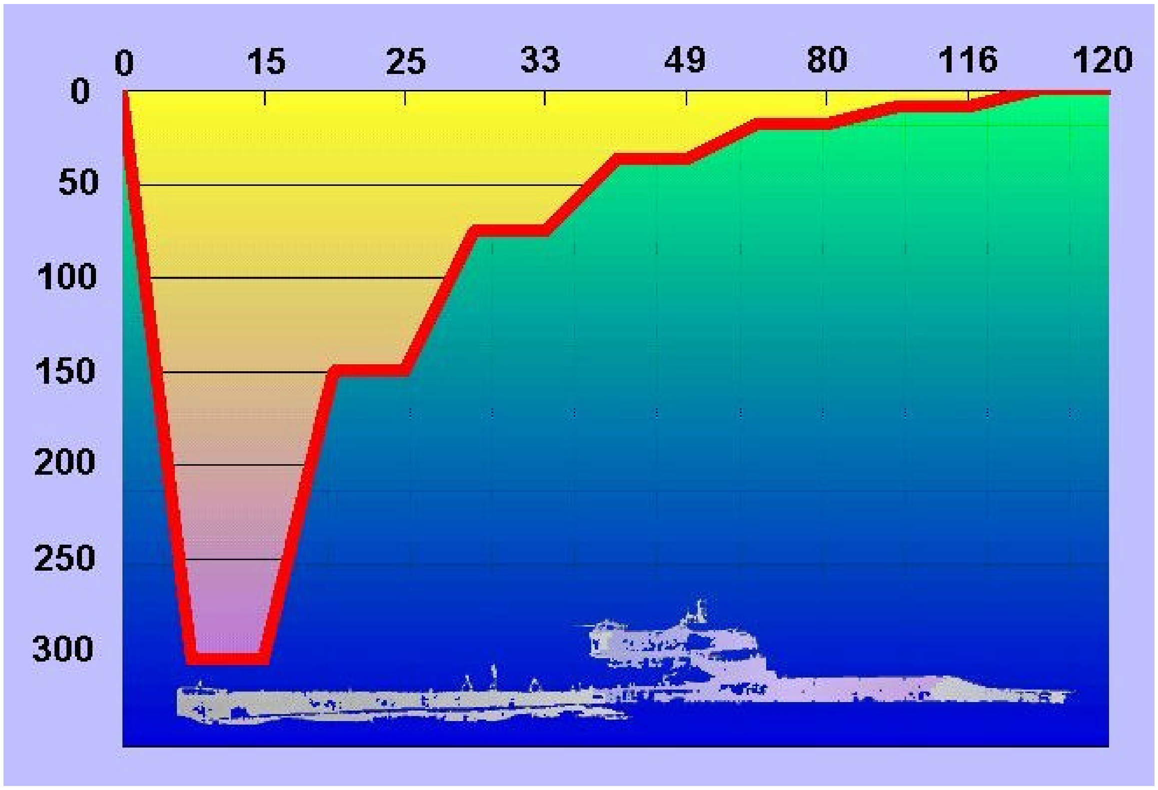
Fellows Presentations

Saturation Diving

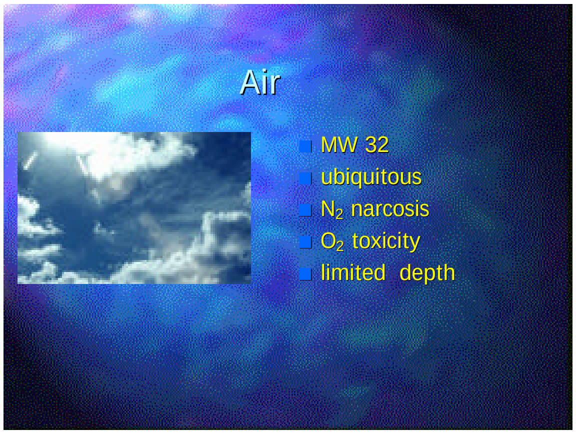
The challenge of diving ever deeper is a goal that intrigues man. The technological advances of the last century have made it possible for humans to descend to depths that were unheard of in earlier times. Yet as new technology becomes available, the physiological problems of making deep dives seem to multiply in kind. In this article we will consider some of the physiologic challenges to deep diving and explore how saturation diving can be used to overcome some of the limitations of diving to deeper depths.

One of the most remarkable early dives was that of Frank Crilley in the salvage of the US submarine F-4 which sank in 304 feet of water off Hawaii in 1915. Using only air as a breathing gas, Crilley spent 11 minutes on the bottom attaching a line to the submarine, and surfaced without ill effect within two hours. For his efforts he was awarded the Medal of Honor. A hypothetical example of the decompression for his dive is given below:



From this illustration one can see that the bulk of time in diving to 304 fsw is spent decompressing. This is not ideal for accomplishing work at depth since most of the time is non-productive spent decompressing rather than working at depth. As one goes deeper the decompression obligation grows logarithmically so that for a 10 minute dive to 1000 fsw, one would theoretically need more than 40 hours of decompression. Clearly something different needed to be done to allow divers to work deeper than 150 fsw.

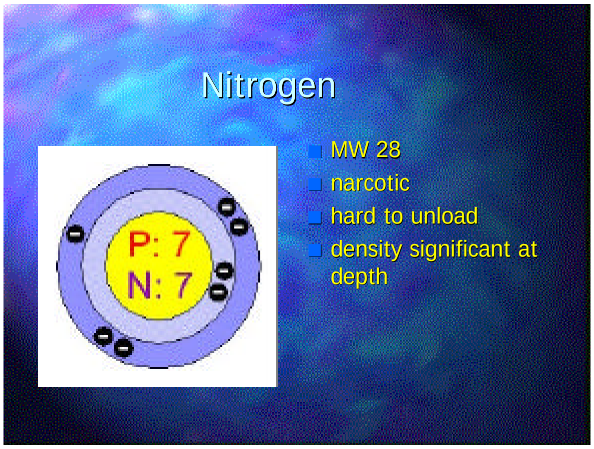
The solution to being able to work at depth is saturation diving. Once the diver has reached the working depth and the tissue compartments are saturated with the breathing gas, no further decompression obligation occurs. It is impossible to supersaturate the tissues. If one can remain at depth and work, rest, eat, etc. a great deal of useful working time is gained. Once this principle was appreciated, saturation dives of a month or more became possible. Then only one decompression period is needed at the end of the dive.



Air

- MW 32
- ubiquitous
- N_2 narcosis
- O_2 toxicity
- limited depth

One of the first challenges is to find a suitable gas to breathe at depth. Since the 1930s it has been recognized that air as a breathing gas has serious limitations at depth. At depths below 150 feet the nitrogen content of air causes nitrogen narcosis or “the rapture of the deep.” The partial pressure of nitrogen in air at 150 feet of seawater (fsw) is 4.38 atmospheres absolute (ATAs). Any time the partial pressure of nitrogen surpasses 4.5 ATAs, nitrogen narcosis can be expected. The condition is characterized by hilarity, inattention to detail, talkativeness, feelings of invulnerability, and eventually inability to follow commands and carry out tasks. For a diver this is a dangerous condition and unfortunately has led to loss of life.

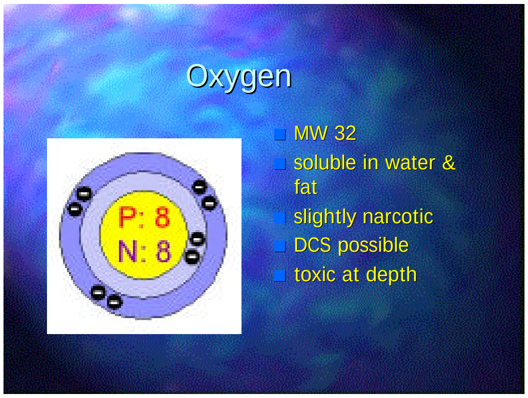


Nitrogen

- MW 28
- narcotic
- hard to unload
- density significant at depth

If nitrogen in air is too dangerous over 150 feet, why not reduce its concentration in air and replace it with another gas? This is key to diving at depth and we will have to consider the properties of the various breathable gases in order to utilize them effectively. Most of the breathable gasses have properties, which might make them desirable in some situations at depth.

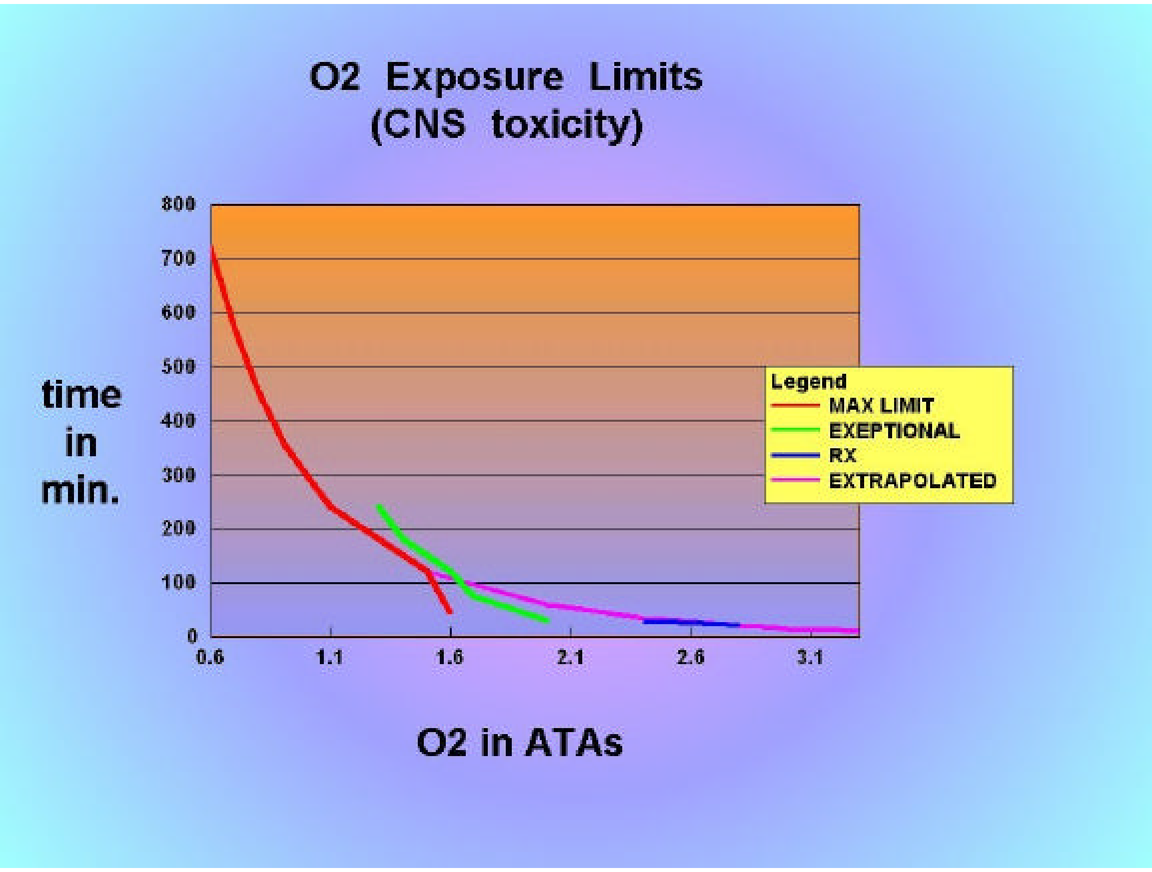
Oxygen is a logical candidate for a diving gas. Easily available and relatively cheap, oxygen has some desirable properties for diving. Since it is required for breathing, it is possible increase the concentration of oxygen in the breathing mix and eliminate some of the problems due to nitrogen. It is the gas of choice at shallow depths for rapid decompression of tissue compartments. If the breathing gas is replaced with 100% oxygen a diffusion gradient is established encouraging the off gassing of nitrogen or other gases which have accumulated in the tissues at depth. Divers take advantage of this situation and may switch to 100% oxygen as a breathing gas at shallow depths, say 20 fsw, in order to shorten the time required for decompression. In treating decompression sickness, oxygen is used to establish adequate tissue oxygenation in tissues in which the circulation is compromised by bubble formation.



Oxygen

- MW 32
- soluble in water & fat
- slightly narcotic
- DCS possible
- toxic at depth

The main limitation of oxygen in deep diving is its central nervous system toxicity. CNS toxicity is characterized by prodromal symptoms of visual disturbance, tinnitus, twitching, nausea, tingling, irritability, and convulsion. The symptoms are extremely variable and the first symptom may be the convulsion, which has led to several unfortunate diving deaths. Some guidelines exist for oxygen partial pressures which should not be exceeded in order to avoid the risk of oxygen toxicity. These are intended as guidelines and not predictors of oxygen toxicity, because of the immense variability in individual susceptibility to oxygen toxicity. The recommended oxygen limits for several sources are illustrated in the graph below:

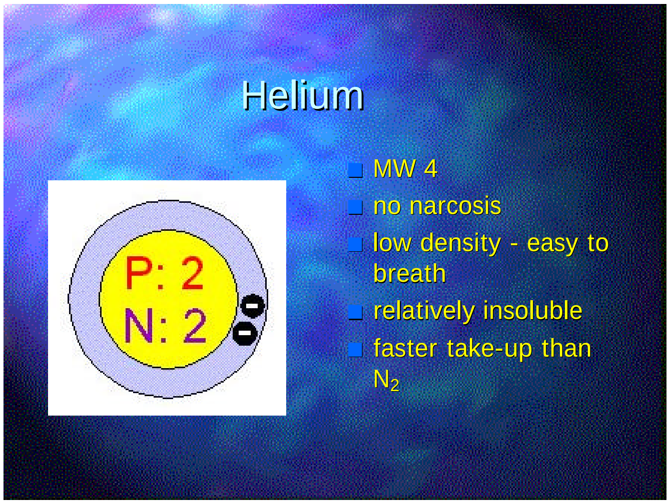


If one stays below the recommended limits, one should be safe.

The O_2 concentration should be kept between 0.21 (normoxic) and 0.48 ATAs. As one goes deeper the difference between hypoxia, normoxia, and oxygen toxicity becomes very small. It is a technical challenge to carefully monitor the oxygen content of the breathing gas and maintain it at the required level. The table below shows the values for desired concentrations:

FSW	ATA	Normoxic O2 %
0	1.0	21.00
33	2.0	10.50
66	3.0	7.00
99	4.0	5.25
165	6.0	3.50
300	10.1	2.08
500	16.2	1.30
1000	31.3	0.67
1500	46.5	0.45
2000	61.6	0.34
2500	76.8	0.27

As one can see from the table above, a concentration of 0.67% O_2 is needed at 1000 fsw to provide a normoxic O_2 level or the partial pressure of O_2 available at the surface. A partial pressure of .1 ATA of O_2 would cause unconsciousness in less than a minute and this would be equivalent to .30% O_2 at 1000 fsw. And a partial pressure of 3 ATA of O_2, or 10% O_2 at 1000 fsw, could cause an oxygen seizure in 30 minutes. Therefore the operational limits of breathable O_2 at 1000 fsw lie well within 0.1 and 10% O_2. In actuality the limits must be much narrower to prevent pulmonary O_2 toxicity, which is seen with O_2 partial pressures greater than .5 ATA when oxygen is breathed more than 24 hours. For saturation diving the limits would need to lie well within 0.1 and 1.34% O_2. The recommended operational range for O_2 concentration is 0.67 to 1.5 % O_2 at 1000 fsw which provides a partial pressure of 0.21 to 0.48 ATA. With such a narrow range of permissible O_2 at depth, accurate monitoring of oxygen levels is of paramount importance.



Helium

- MW 4
- no narcosis
- low density - easy to breath
- relatively insoluble
- faster take-up than N_2

Because of the unacceptable narcotic properties of nitrogen, helium has been used as the inert gas below 150 fsw. With a molecular weight of 4 helium is easy to breathe at depth and has the advantage of producing no narcosis. It is relatively insoluble and crosses tissue barriers more rapidly than nitrogen with a faster uptake. When switching from nitrogen as an inert gas to helium, the helium will rapidly move into the tissues before the nitrogen can be off-gassed. A condition known as isobaric counterdiffusion can be created where the total gas pressure of tissue compartments reaches supersaturation because the nitrogen has not left the tissue and the helium has moved into the tissue. As a result of this elevated gas pressure bubbles may form typically causing skin and inner ear symptoms. The tissue half times for helium and nitrogen for four theoretical compartments are illustrated here:

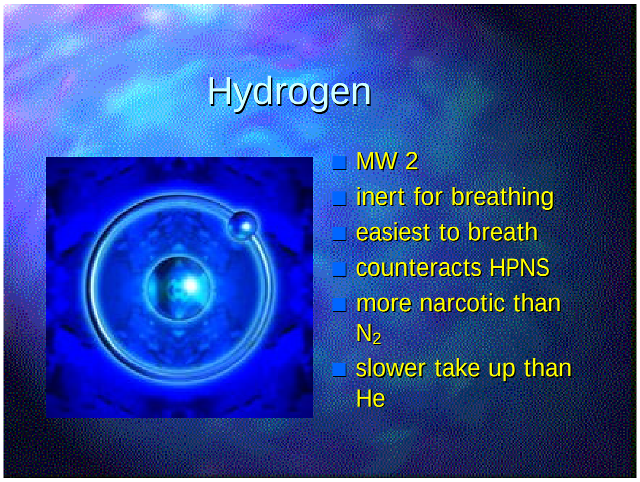
Cmpt	$t_{1/2}N_2$	$t_{1/2}He$	
a	25	20	min
b	145	80	
c	385	160	
d	670	240	

By slowly switching to helium counterdiffusion problems can be avoided.

When helium was first employed it was possible to dive to depths deeper than ever before achieved. When divers under the direction of Dr. peter Bennett at Duke reached the equivalent of 2000 fsw in a “dry” or chamber dive breathing a mixture of helium and oxygen (heliox), bizarre neurologic symptoms were noted. These included nausea, vomiting, headache, tremors, prostration, and seizure-like activity. This was dubbed high pressure nervous syndrome (HPNS). The symptoms were severely limiting and thought to be due to the pressure or a direct effect of helium. Now we think that the helium allows for an “unmasking” of the normal sedating effect of nitrogen when nitrogen is excluded from the breathing mix. The pathophysiology is not fully understood and nerve cell membrane or synaptic membrane changes and ion fluxes have been implicated.

By slowing the descent rate to 8 fsw/hr or less HPNS can be minimized. There is also some recovery at depth, so by allowing for long compression stages divers can have time to adapt to some of the HPNS symptoms. Adding 5% nitrogen to the breathing mix helps, or alternatively hydrogen can be added. There is also some individual susceptibility to HPNS with some divers being much more susceptible than others. Diver selection can also aid in reducing the incidence of HPNS.

Hydrogen has some characteristics that offer benefits to deep divers. Because of it’s low molecular weight of 2 it is easier to breathe at depth than helium. Unfortunately hydrogen has more narcotic effect than nitrogen and so can’t be used as the main inert gas at depth. Hydrogen’s narcotic effect can be used to advantage to counteract the HPNS effects of helium. A typical gas mix would be 49% hydrogen, oxygen to provide 0.48ATA at depth, and the remainder of the gas as helium. Using a H_2-He-O_2 mix depths of 2300 fsw have been reached. Hydrogen diffuses slower than helium so the decompression times are longer for this gas.



Hydrogen

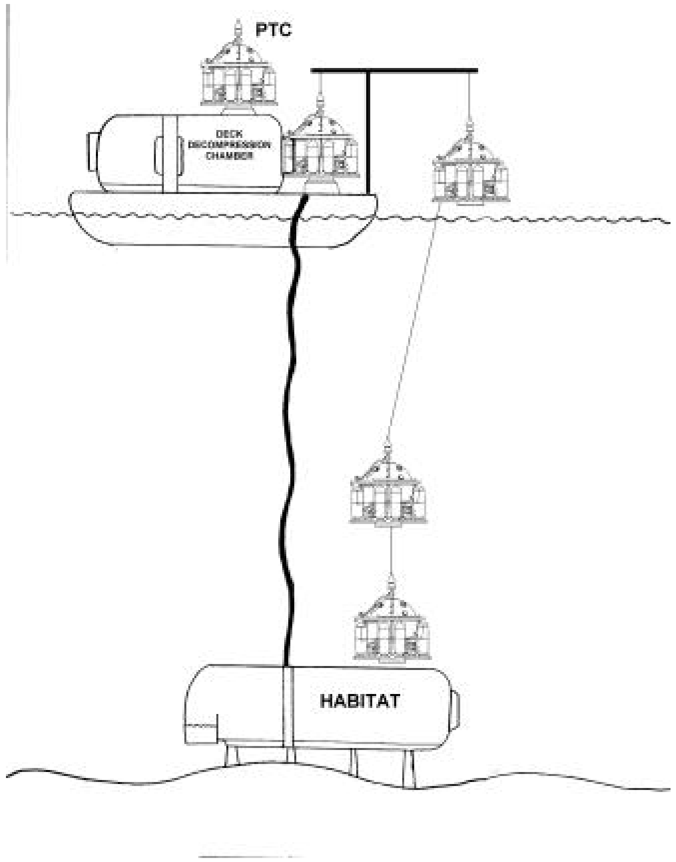
- MW 2
- inert for breathing
- easiest to breath
- counteracts HPNS
- more narcotic than N_2
- slower take up than He

Now that appropriate gas mixtures can be selected for saturation diving, the diver needs an underwater habitat. The saturation diving system has three components; 1) a deck decompression chamber (DDC), 2) a personnel transfer chamber (PTC), and 3) the underwater habitat. The diver is compressed to depth in the deck decompression chamber. This warm and dry environment allows for hot meals, personal amenities such as toilets and showers, and medical help is readily available if needed. Once the diving depth has been reached in the DDC, the divers transfer to the personnel transfer chamber (PTC) for the descent to depth. The PTC is locked onto the habitat and the divers enter the habitat. From the habitat the divers can make limited excursions avoiding a decompression obligation. Divers may stay in the surface supplied habitat for weeks, making daily excursions of eight hours or more to accomplish their underwater tasks maximizing the use of resources.

From the habitat the divers can make no-decompression excursions. Theoretically it would be possible to ascend or descend to any depth from the habitat and decompress accordingly. For practical reasons and because of a lack of reliable decompression tables at deeper depths, this is usually not done. Given a known depth and breathing mixture, a safe upward and downward excursion with no decompression stops can be made using published or proprietary tables.

Saturation Depth	Downward Excursion	Upward Excusrsion
0	29	
30	40	29
60	48	37
100	58	47
200	77	65
300	92	80
500	116	104

Examples of No-Decompression Saturation Diving Limits from US Navy Tables



When a diver needs to surface, it is done in the PTC compressed to depth. The PTC is then locked onto the DDC and the diver can spend several days decompressing in the safety of the DDC. If the dive work has been completed, the ship can be underway whilst the divers decompress – a process that can take several days. Decompression rates are very slow, approximately one hour for every meter of saturation depth. A 2000 fsw dive might require nearly a month for decompression! By increasing the inhaled O_2 content to 0.5 ATA some time can be eliminated from the decompression obligation, but it is still a lengthy process.

Saturation diving operations are very expensive and it is important to maximize the working time for divers on the bottom. When it is necessary to use more than one crew at depth the divers can use the PTC to shuttle back and forth between the habitat and the DDC. After the first crew is in the habitat, the second crew can be compressing in the DDC. The second crew then enters the habitat and the first crew ascends to the DDC for decompression. In this way the time spent productively on the bottom is maximized.

From this discussion it can be seen that saturation diving is limited by human physiology. When taken into account the saturation dive is a lengthy expensive process in which the body is stressed to its limit. Because of the limitations of the breathing gases available, it is likely that submersibles and robots will be used for depths deeper than 2000 fsw for some time to come.

For further reading:

Diving Medicine, 3rd Edition, Alfred A. Bove, W. B. Saunders, Company, Philadelphia, 1997

The Bends. Compressed Air in the History of Science, Diving, and Engineering. John L. Phillips, Yale University Press, New Haven, 1998

U.S. Navy Diving Manual, Revision 4, 1999

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