COMPARATIVEPROPERTIES

Nitrogen Substitutions — which gas is best?

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Nitrogen is limited as an inert gas for diving. We all know that increased pressures of nitrogen beyond 200 feet (60m) lead to excessive euphoria, and reduced mental and physical functional ability, while beyond 600 feet (180m) loss of consciousness results. Individual tolerances vary widely, often depending on activity. Symptoms can be marked at the beginning of a deep dive, gradually decreasing with time. Flow resistance and the onset of turbulence in the airways of the body increase with higher breathing gas pressure, considerably reducing ventilation with nitrogen-rich breathing mixtures during deep diving. Oxygen is also limiting at depth for the usual toxicity reasons. Dives beyond 300 feet (90m) requiring bottom times of hours need to employ lighter, more weakly reacting, and less narcotic gases than nitrogen, and all coupled to reduced oxygen partial pressures.

A number of inert gas replacements have been tested, such as hydrogen, neon, argon, and helium, with only helium and hydrogen performing satisfactorily on all counts. Because it is the lightest, hydrogen has elimination speed advantages over helium, but, because of the high explosive risk in mixing hydrogen, helium has emerged as the best all-around inert gas for deep and saturation diving. Helium can be breathed for months without tissue damage. Argon is highly soluble and heavier than nitrogen, and thus a very poor choice. Neon is not much lighter than nitrogen, but is only slightly more soluble than helium. Of the five, helium is the least and argon the most narcotic inert gas under pressure.

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Saturation and desaturation speeds of inert gases are inversely proportional to the square root of their atomic masses. Hydrogen will saturate and desaturate approximately 3.7 times faster than nitrogen, and helium will saturate and desaturate some 2.7 times faster than nitrogen. Differences between neon, argon, and nitrogen are not significant for diving. Comparative properties for hydrogen, helium, neon, nitrogen, argon, and oxygen are listed in figure one. Solubilities, S, are quoted in atm^{-1}, weights, A, in *atomic mass units*, and relative narcotic potencies, n, are dimensionless (referenced to nitrogen in observed effect). Least potent gases have the highest index, **v,** also in figure one.

The size of bubbles formed with various inert gases depends upon the amount of gas dissolved, and hence the solubilities. Higher gas solubilities promote bigger bubbles. Thus, helium is preferable to hydrogen as a light gas, while nitrogen is preferable to argon as a heavy gas. Neon solubility roughly equals nitrogen solubility. Narcotic potency correlates with lipid (fatty tissue) solubility, with the least narcotic gases the least soluble.

Different uptake and elimination speeds suggest optimal means for reducing decompression time using helium and nitrogen mixtures. Following deep dives beyond 300 feet (90m) breathing helium, switching to nitrogen is without risk, while helium elimination is accelerated because the helium tissue-blood gradient is increased when breathing an air mixture. By gradually increasing the oxygen content after substituting nitrogen for helium, the nitrogen uptake can also be kept low. Workable combinations of gas switching depend upon the exposure and tissue compartment controlling the ascent.

In deep saturation diving, normoxic breathing mixtures of gases are often advantageously employed to address oxygen concerns. A normoxic breathing mixture, helium or nitrogen, reduces the oxygen percentage so that the partial pressure of oxygen at the working depth is the same as at sea level, the obvious concerns, again, hypoxia and toxicity.

Critical tensions can be employed in helium saturation diving in much the same fashion as nitrogen diving. A critical tension, recall, is the maximum permissible value of inert gas tension (M-value) for a hypothetical tissue compartment with specified halftime. An approach to helium exchange in tissue compartments employs the usual nitrogen set with halftimes reduced by 2.7, that is, the helium halftimes are extracted from the nitrogen halftimes following division by 2.7, and the same critical tension is assumed for both gas compartments. Researchers have tested schedules based on just such an approach. Tissue tensions scale as the relative proportion of inert gas in any mixture.

Helium (normal 80/20 mixture) nonstop time limits are shorter than nitrogen, and follow a $t^{1/2}$ law similar to nitrogen, that is, depth times the square root of the nonstop time limit is approximately constant. Using standard techniques of extracting critical tensions from the nonstop time limits, fast compartment critical tensions can be assigned for applications. Modern bubble models, such as the varying permeability model, have also been used strategically in helium diving.

Today, the three helium and nitrogen mixtures (nitrox, heliox, trimix) are employed for deep and saturation diving, with a tendency towards usage of enriched oxygen mixtures in shallow (recreational) diving. The fourth hydrogen mixture (hydrox) is much less commonplace.

NITROX

Mixtures of oxygen and nitrogen with less oxygen than 21% (pure air) offer protection from oxygen toxicity in moderately deep and saturation diving. Moderately deep here means no more than a few hundred feet. Hypoxia is a concern with mixtures containing as much as 15% oxygen in this range. Saturation diving on oxygen-scarce nitrox mixtures is a carefully planned exposure. The narcotic effects of nitrogen in the 100 feet (30m)to 200 feet (60m) depth range mitigate against nitrox for deep diving.

Diving on enriched nitrox mixtures need be carefully planned exposures, but for opposite reason, that is, oxygen toxicity. Mixtures of 30% or more of oxygen significantly reduce partial pressures of nitrogen to the point of down loading tissue tensions compared to air diving. If standard air decompression procedures are employed, enriched nitrox affords a diving safety margin. However, because of elevated oxygen partial pressures, a maximum permissible depth (floor) needs be assigned to any enriched oxygen mixture. Taking 1.6 atm (52.8 feet/16m) as the oxygen partial pressure limit, the floor for any mixture is easily computed. As any nitrox certified diver knows, enriched nitrox with 32% oxygen is floored at a depth of 130 feet (40m) for diving. Higher enrichments raise that floor proportionately.

Decompression requirements on enriched nitrox are less stringent than air, simply because the nitrogen content is reduced below 79%. Many equivalent means to schedule enriched nitrox diving exist, based on the standard Haldane critical tension approach. Air critical tensions can be employed with exponential buildup and elimination equations tracking the (reduced) nitrogen tissue gas exchange, or equivalent air depths (always less than the actual depths on enriched nitrox) can be used with air tables. The latter procedure ultimately relates inspired nitrogen pressure on a nitrox mixture to that of air at shallower depth (equivalent air depth). For instance, a 74/26 nitrox mixture at a depth of 140 feet (42m) has an equivalent air depth of 130 feet (40m) for table entry. Closed breathing circuit divers have employed the equivalent air depth approach for many years.

HELIOX

The narcotic effects of nitrogen in the several hundred feet range prompted researchers to find a less reactive breathing gas for deeper diving. Tests, correlating narcotic effects and lipid solubility, affirm helium as the least narcotic of breathing gases, some four times less narcotic than nitrogen according to Bennett. Deep saturation and extended habitat diving, conducted at depths of 1,000 feet (300m) or more on helium/oxygen mixtures by the US Navy, ultimately ushered in the era of heliox diving. For very deep and saturation diving above 700 feet (212m) or so, heliox remains a popular, though expensive, breathing mixture.

Helium uptake and elimination can also be tracked with the standard Haldane exponential expressions employed for nitrogen, but with a notable exception. Corresponding helium halftimes are some 2.7 times faster than nitrogen for the same hypothetical tissue compartment. Thus, at saturation, a 180 minute helium compartment behaves like a 480 minute nitrogen compartment. All the computational machinery in place for nitrogen diving can be ported over to helium nicely, with the 2.7 scaling of halftimes expedient in fitting most helium data.

TRIMIX

Diving much below 1400 feet (424m) on heliox is not only impractical, but also marginally hazardous. High pressure nervous syndrome (HPNS) is a major problem on descent in very deep diving, and is quite complex. The addition of nitrogen to helium breathing mixtures (trimix), is beneficial in ameliorating HPNS. Trimix is a useful breathing mixture at depths ranging from 500 feet (150m) to 2000 feet, (600m) with nitrogen percentages usually below 10% in operational diving, because of narcotic effect.

Inert Gas and Oxygen Molecular Weights, Solubilities, and Narcotic Potency.

	Hydrogen	Helium	Neon	Nitrogen	Argon	Oxygen
A (amu) Atomic Mass Units	2.02 amu	4.00 amu	20.18 amu	28.02 amu	39.44 amu	32.00 amu
Solubility (atm-1) Blood Oil	.0149 .0502	.0087 .0150	.0093 .0199	.0122 .0670	.0260 .1480	.241 .1220
V	1.83	4.26	3.58	1.00	0.43	

FIGURE 1

INERT GAS AND OXYGEN MOLECULAR WEIGHTS, SOLUBILITIES, AND NARCOTIC POTENCY.

Decompression concerns on trimix can be addressed with traditional techniques. Uptake and elimination of both helium and nitrogen can be limited by critical tensions. Using a basic set of nitrogen halftimes and critical tensions, and a corresponding set of helium halftimes approximately three times faster for the same nitrogen compartment, total inert gas uptake and elimination can be assumed to be the sum of fractional nitrogen and helium in the trimix breathing medium, using the usual exponential expressions for each inert gas component. Such approaches to trimix decompression were tested by researchers years ago, and many others after them.

HYDROX

Since hydrogen is the lightest of gases, it is reasonably expected to offer the lowest breathing resistance in a smooth flow system, promoting rapid transfer of oxygen and carbon dioxide within the lungs at depth. Considering solubility and diffusivity, hydrogen uptake and elimination rates in blood and tissue should be more rapid than nitrogen, and even helium. In actuality, the performance of hydrogen falls between nitrogen and helium as an inert breathing gas for diving.

Despite any potential advantages of hydrogen/oxygen breathing mixtures, users have been discouraged from experimenting with hydrox because of the explosive and flammable nature of most mixtures. Work in the early 1950s by the Bureau of Mines, however, established that oxygen percentages below the 3%-4% level provide a safety margin against explosive and flammability risks. A 97/3 mixture of hydrogen and oxygen could be utilized at depths as shallow as 200 feet (60m), where oxygen partial pressure equals sea level partial pressure. Experiments with mice also indicate that the narcotic potency of hydrogen is less than nitrogen, but greater than helium.

With more and more divers pushing into depths that only a few years ago were unheard of, picking the correct gas mixture becomes crucial both during the dive and during decompression. Extensive experimentation is on going using all of the inert gases. However, we have attained an acceptable level of knowledge and understanding to allow us to make educated choices depending on the particular dive profile and goals.

As more of us dive specialized mixes, we will undoubtedly increase our understanding and, therefore, our safety. For now, do the research, talk to the experts and make informed choices before you delve into depth previously reserved for marine life. DT

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