Workshop Findings:

Evaluating Enriched Air ("Nitrox") Diving Technology

Reported by R.W. Hamilton, Ph.D.
Workshop General Chairperson

Preface

This is a report of the major findings of a workshop convened to address current controversies about the increasingly popular practice of scuba diving with oxygen-enriched air, or "nitrox," gas mixtures by non-professional "sport" or "recreational" divers. The workshop was held just before the 1992 DEMA show, the annual convention of the Diving Equipment Manufacturers Association and the premier recreational show held in the United States.

Preparations for the DEMA show highlighted the controversy over the promotion of enriched air diving among recreational divers. It was felt that part of the controversy was related to lack of information about the practice by some of the critics, but it also seemed clear that some current enriched air practices were likely to be unsafe and hence unacceptable.

This report presents the sentiment and the significant conclusions of the workshop, as interpreted by an independent senior observer (R.W.H.) who is well acquainted with the issues and the participants, but who has no vested interest in, and in fact is personally quite critical of, some of the prevailing practices.
The report is neither a detailed "proceedings" nor a strict consensus, but&endash;with the help of chairmen, organizers, and others&endash;it is an honest attempt to reflect the general opinion of the highly qualified group of specialists, experts, and experienced practitioners, as they addressed the major issues. [The author has exercises his prerogative of using the term "enriched air" where it seems appropriate.]

The program was divided into sections which addressed the different aspects of enriched air diving, and thus it dealt with the separate issues individually. The objective was to come up with guidelines or standards for enriched air diving that will ensure the safety of those practicing it, will protect those whose equipment and efforts are engaged in it, and&endash;where it makes sense&endash;will satisfy its critics.
It is meaningful to point out issues **not** addressed by the workshop. Among these are "high tech" diving, including the use of helium-nitrogen-oxygen trimixes for diving beyond the air range, and the use of oxygen in the water for decompression. Also, the organizational "charter" for the program did not intend or attempt to draw the established recreational diving training organizations into accepting or adopting enriched air into their existing programs, nor to expand the established boundaries of "recreational diving" to include enriched air. We addressed the technology as currently practiced; what others choose to do with it is up to them.

Although some issues were left with questions, and the need to acquire additional data was identified, several issues were clearly and definitely resolved. Some others were give provisional solutions. A working group was set up to tackle getting the information needed to settle the unresolved questions.
*NOTICE: This is a **policy** document. It is neither a cookbook on how to do it, nor a standard on necessary limits for enriched air diving; it is not intended for the shop or the field. The report does, however, offer considerable information and some "food for thought" for decision makers. This report is not regarded as conclusive or comprehensive, but rather as a good start toward providing a solid foundation for the practice of diving with enriched air.*

Program

The planners attempted to included in the Workshop experts in the various facets of the field. Despite the short time to do this and the time pressure caused by commitments to the DEMA show, this worked out quite well. Leading experts on mixing and handling oxygen and gases rich in oxygen, on compressors, lubricants, gas systems, and scuba tank integrity were all present. Representatives from manufacturers of recreational diving equipment and from training agencies were present. Also participating were lawyers specializing in recreational diving, and experts on diving physiology, commercial diving, oxygen, decompression, and dive computers, as well as managers of scientific diving programs. A large fraction of the audience were people experienced in diving, teaching, installing systems for, and using enriched air; for the record many of these were trained by one or both of the existing these air ("nitrox") agencies.

Introduction

The "enriched air" gases in question are mixtures of air and oxygen with resulting percentages ranging between about 30 to 50% oxygen, balance nitrogen. These mixes are often called "nitrox," but that term also applies-more appropriately to mixtures with less oxygen than air. Dr. Tom Hennessy suggests calling it "airox."

The oxygen-enriched mixtures are breathed primarily to reduce the decompression obligation or, conversely, to improve the reliability of decompression using enriched air but carried out as if the mix were air. Another objective is to reduce narcosis. This is widely assumed to be effective on a partial pressure basis, but an attempt to measure this objectively in the laboratory did not show any difference in performance when some of the nitrogen in a breathing mix was replaced with oxygen (Linnarsson *et al*, 1990). Another reason for using enriched air "nitrox" is that it is becoming very fashionable.

Physiological limitations to the use of enriched air are based on oxygen toxicity, and there are some questions about the decompression techniques used. The most important aspect of oxygen toxicity is central nervous system (CNS) involvement, which can result in an epileptic-like convulsion that can be fatal due to drowning if it occurs in the water. A second-order effect is the possible toxicity due to longer-range exposure doses of many hours or days, and the possibility that oxygen exposure during diving may reduce slightly a diver’s tolerance to treatment for DCS should that be needed. The decompression question revolves around whether a decompression table calculated on the basis of nitrogen partial pressure (the "equivalent air depth") will be as reliable as the original table.

Of equal concern are the hazards of mixing and handling oxygen and mixtures rich in oxygen. In order to mix enriched air, it is necessary to handle pure oxygen at high pressure. The procedures for handling oxygen safely are well established in industry, although there is concern that proper oxygen handling procedures may not be well known to many of the enriched air blenders. While enriched air mixtures are definitely less difficult to handle than oxygen, there are no clear guidelines on how to handle blends in the range between air (defined as 19 to 23% oxygen) and about 50% oxygen. The big issue here is that these mixes are being made and used with tanks and equipment designed and manufactured for use with air in recreational diving. The manufacturers perhaps perceive that the use of enriched air in regular scuba gear exposes them to liability. Is it acceptable for enriched air to be mixed and/or stored in standard scuba gear, and can it safely be breathed using ordinary scuba apparatus? Would this be acceptable if proper nonmetallic parts and lubricants compatible with oxygen were to be used?

Another issue is the belief that the high oxygen will cause excessive tank corrosion and deterioration of nonmetallic materials. Still another issue is the choice and use of compressors, both for preparing the compressed air used as the basis for the mix and for boosting the completed mix to the pressure required for filling scuba tanks. If air is "cleaned" by filtration, how clean is clean?

The other major concern about enriched air diving relates to the divers; specifically whether their training is appropriate, and whether they are adequately supervised and certified. This applies up the line to instructors and to the training agencies, and also to the organizations dispensing the mixtures. What is needed to ensure that divers get the necessary training, that they are certified by accountable agencies, and that the special mixtures are dispensed only to qualified divers?

It was pointed out to the group that many of the issues are addressed in some detail in the Harbor Branch Workshop on enriched air diving, (Hamilton, Crosson and Hulbert, 1989). Other writings that have been used as indicators of concern about enriched air included the editorial by Dr. Peter Bennett in *Alert Diver* (1991), the report by Dr. Bove in *Pressure* (1992), the essay by Drew Richardson in *Undersea Journal* (1991), the letter to *Pressure* by Dr. Tom Hennessy (1991b) and his earlier article (1991a). Another "issue" was the warning distributed by DEMA on 1991 December 17 concerning the use of enriched air in standard scuba gear.

Survey of enriched air experience

In order to begin with an understanding of the prevailing level of experience, the Workshop made an effort to estimate in broad terms how much mixing and diving has been done with enriched air mixtures. We conducted two surveys, one using an overly complicated form that sought details about both the mixing and the diving, the other a telephone survey of known high-level users. After eliminating the overlap between the two surveys, we identified approximately 28,000 enriched air dives or tank fills (some tanks of enriched air were used for other types of diving), most specifically documented in logbooks and most performed in the last five years. Most of these were organized users who practice consistent procedures, use some sort of record-keeping, and have a special concern for safety in order to protect their operations as well as their divers. A detailed analysis of the survey is not yet available.
The results have no statistical meaning, but a review of the reported incidents is helpful. No problems were reported with mixing and handling the gases. One respondent mentioned unspecified symptoms of oxygen toxicity, and another mentioned the occurrence of decompression sickness (DCS). In a rough comparison, the incidence of DCS appears to be less than would be expected from a similar set of straight air dives. Several respondents mentioned DCS incidents before switching to enriched air and none after.
Interestingly, several respondents who did not report DCS or oxygen symptoms in their own activities said they knew of them occurring to others. In addition to the more-or-less organized operations covered, there appears to be a widespread use by independent divers of "home brew" enriched air mixtures.
Included in the survey are about 5,000 dives performed by scientific diving organizations. In one set, two cases of DCS were reported in a group of 3,200 dives. Although these occurred in stressful dives, they are normal for such operations and not regarded as a cause for questioning the method. The same group also reported "nitrox headaches" in some divers; the manufacturer of the diving masks used offered the opinion (after the Workshop) that this was very likely due to divers not accustomed to full-face masks pulling the straps too tight (Bev Morgan, Diving Systems International, personal communication, 92 Jan).
Another scientific group mentioned one case of DCS in more than 1,100 dives. One convulsion was reported, at 80 fsw at a PO_2 of 1.26 atm in a diver later found to be epileptic and on anti-seizure medication at the time. (He was rescued without injury.)

The above is in addition to many years of commercial experience with enriched air mixtures, using both mixing and diving methods not particularly relevant to the issues of this Workshop. This commercial experience base incorporates several times an many dives, probably more than 100,000, and the results have disclosed no outstanding physiological problems with exposures to enriched air mixtures. Enriched air diving is not universal in the commercial diving industry, but it is well accepted where used; the only issue there is economic&endash;whether the extra cost and complexity are justified by the improved efficiency.

To expand the survey we asked the Diver's Alert Network (DAN) for any cases of DCS or accidents in their files known to involve enriched air. Eight cases of DCS were reported; five were from more-or-less

normal procedures, although we do not know either the exact profiles followed nor the composition of the mixes used. Three other cases involved special circumstances such as rapid ascents. Six of the cases were by spearfishermen, the other by a wreck diver at 150 fsw (where enriched air is of little value unless oxygen limits are greatly exceeded); five are documented as using "home brew" mixtures. These cases are probably not included in the survey mentioned earlier, and we have no idea what the "denominator" for this set of cases is. Given the aggressive diving and somewhat casual decompression practices of diving fishermen traditionally, this DCS is not unexpected. In any case this serves to confirm that enriched air diving is part of the real world, and that DCS should be expected and does occasionally occur.
In another case a diver breathing enriched air died as a result of a shark attack.

The intent of this report is not to included anecdotal reports from sport divers using it or those promoting it, on how great enriched air is. One report merits an exception to this. In a tidy, well-documented operation, Larry Elsevier supplies enriched air mixtures to hard-working professional harvest divers in the Puget Sound area. He reports better productivity, fewer health problems, and that divers previously totally exhausted at the end of a day of diving with air can have a family life when they use enriched air.

Diving physiology: Oxygen

A review of the physiology of exposure to high oxygen levels showed that the major effort should be on reducing the possibility of CNS toxicity that could lead to a seizure, which could easily be lethal if occurring in the water. Susceptibility is highly individual, is affected by a host of factors such as anxiety, exercise, cold and especially CO_2, and usually comes on without warning. Gas-conserving breathing patterns resulting in lower lung ventilation and a tendency to retain CO_2 (in some divers) are added risk factors.

The oxygen exposure limits in the soon-to-be-released *Third Edition of the NOAA Diving Manual* (1991) were endorsed as appropriate **physiological** limits. This sets an upper limit of 1.6 atm PO_2 for a diver operating under ideal conditions, with a maximum duration at that level of 45 minutes; lower PO_2 levels allow longer exposures. Several participants felt that although these limits are acceptable physiologically, it may not be safe to endorse them for use by minimally trained divers, and lower limits should be proposed. There was concern because it is well known that divers will push any limit as far as they can without technically violating it. This was regarded as an issue more related to discipline or training than physiology, but it is not to be ignored. Another point made in this discussion is that a quantitative algorithm for ongoing monitoring of CNS toxicity is badly needed. It should be made clear, again, that the use of trimix, high-oxygen intermediate decompression mixes, or breathing 100% oxygen in decompression were **not** discussed at this workshop.

Callout Box: *"Oxygen is addictive and deadly. Everyone who uses it will eventually die."*

Dr. R.W. Bill Hamilton, Workshop Chairperson &endash; lighter moments.

In addition to CNS, the NOAA procedures take "whole body" or lung exposure into account for a single day; for multiday exposures the Repex limits can also be used (Hamilton, 1989). Along this line, Dr. Bennett (1991) raised the question of whether a diver having dived on enriched air would be compromised in the treatment which could be used in the event the diver were to get DCS; his concern was because of the oxygen exposure during the enriched air dives. A hypothetical "typical" intensive day, including four enriched air dives, was examined. These dives caused an estimated 141 OTU (oxygen tolerance units, same as UPTD). For treatment, the first day of exposure according to standard practice can be up to about 1,400 OTU, an exposure which should give a distinct but tolerable degree of stress or reduction in vital capacity, and which is regarded as acceptable for treatment. An extra 141 units has some effect, but not much. If there is a delay of several hours before chamber treatment begins, the effect will be negligible.

Advocates mentioned that if the tradeoff for this relatively light oxygen exposure is a reduced risk of DCS or perhaps the need for one less decompression during the day (because bottom times are longer), it is likely to be well worth it. Other dive-in treatment scenarios could allow the oxygen exposure to reach a significant level, but these are not likely to be encountered in recreational divers, and they can be managed adequately by experienced diving doctors.

Others at the workshop challenged a comment that diving with enriched air would condition the spinal cord or other critical tissue to better deal with stress by virtue of the higher oxygen environment. It is unlikely that a sufficient oxygen difference would prevail at the cellular level to be of significant benefit. Dr. Bove mentions (1992) the "uncertain effects of increased oxygen partial pressures...." The **mechanism** of oxygen toxicity is still uncertain, but for the levels involved here, its effects are regarded as being well known, as are the means of dealing with it, for normal, healthy divers.

Diving physiology: Decompression

Enriched air decompressions are almost all calculated or determined on the basis of the inert gas (nitrogen) partial pressure. There are some "theoretical" reasons to question the validity of this method, but how well has it worked in practice? The efforts of the workshop and the studies cited do not intend to belittle serious questions that need to be considered in a thorough review, but the overwhelming balance of evidence leaves little cause to be concerned about decompression from enriched air dives.
Certainly the survey provides no support for questioning this practice, and a similar conclusion can be drawn from the extensive commercial experience; there have been no problems with decompression that would suggest that the "equivalent air depth" principle is invalid. Vann, in the Harbor Branch Workshop (1989), examined the experimental work directed toward this question and concluded that, again, there is no meaningful evidence that the principle does not work.

The point is occasionally made that high levels of oxygen cause vasoconstriction, and that this may impede the outgassing of nitrogen. Both animal experiments and human experience see this effect, but it does not appear to have an impact on decompression until levels above about 2.0 atm PO_2 are reached; this is a level substantially above the limit for enriched air diving. If oxygen’s vasoconstriction is causing a problem, its replacement of inert gas is even more prominent, and this benefit appears to overwhelm whatever vasoconstriction problem may exist. Experience with treatment of DCS, a more complex situation, also is consistent with the beneficial effects of oxygen, even at PO_2s above 2.0 atm.
Another concept of oxygen behavior in decompression assumes that when oxygen is high enough, it is not all consumed in the tissue, and some may act temporarily as an inert gas. No data bearing on this was mentioned at the Workshop, but from experience, if there is such an effect, it appears to be small in the limited oxygen range used with enriched air.

On more practical decompression matters, an examination of the equivalent air depth by Hennessy mentioned several theoretical concerns (1991a; 1991b), and these were used as a guide to Workshop deliberations. These points were addressed specifically, but in summary most of them appear to be of second-order importance in any case. Some could be dealt with just by making different but equally realistic assumptions. Not considered in Hennessy’s analysis is the fact that the diver decompression from an equivalent air depth dive is breathing a mixture richer in oxygen than air, and thus has an important decompression advantage over the air diver. Further, it is well established that&endash;everything else being equal&endash;the shorter the dive, the better the decompression. This is exemplified by the "limiting line" concept with most tables; the longer tables are not as reliable. Enriched air dives are shorter than their companion air dives. Also, an enriched air dive is more nearly a "shallow, long" dive than the air companion which is more "deep, short." The latter type has a relatively higher incidence of neurological DCS. All these contribute to making the equivalent air depth dive probably a little better or more conservative from a decompression perspective than the equivalent air dive.

Dr. Hennessy does make some useful suggestions (1991b) for implementation of equivalent air depth dives. When calculating a repetitive dive, the diver should assume that the dive before was an air dive and should make only two dives per day. He also recommends developing tables specifically calculated for enriched air mixtures. His suggested limit of 1.8 atm and a depth of 46 msw (150 fsw) with 32% oxygen exceeds significantly the NOAA limits (1.6 atm) endorsed by the Workshop and is not recommended.
A most important point about the equivalent air depth method of decompression is that the decompression, even though it may be a little better than the equivalent air dive, is still limited in quality by the air table used. The longer USN Standard Air tables are not particularly reliable.

In an effort to quantify these effects, some standard air dives were compared with their enriched air equivalents using maximum likelihood statistics. **The comparison showed that enriched air dives are uniformly less risky than their air counterparts.** For example, for 130 fsw/60 min. the air dive has almost twice the predicted incidence of DCS as the enriched air dive. This likelihood analysis was calibrated by DCIEM on a data set of some 2,500 dives.

It was agreed and seems quite clear, with no real cause for argument except the oxygen exposure issue discussed above, that the correct **treatment** for a diver who has contracted DCS from an enriched air dive (or a series of them) should be one of the standard treatments used for air diving. Delaying the start of treatment to debate this issue would be irresponsible.

An attractive way to decompress from an enriched air dive would be by means of a dive computer. Currently some divers use air-based computers but breathe enriched air mixtures; performed correctly this results in a conservative decompression, whether or not stops are required. Two computers are available that consider enriched air mixtures specifically. A modified version of the Orca Delphi is programmed for 36% oxygen enriched air and is limited to that mix (or others with higher oxygen). A new computer, the Ace Pro-File by the British company Quatek, Ltd., allows the mixture to be set. The Pro-File offers an oxygen sensor as an option, and claims monitoring for CNS and long term oxygen toxicity. If done effectively this is a feature recommended for all variable-oxygen dive computers. Education of divers in avoiding exposure to toxicity is needed in any case.

Mixing and handling enriched air mixtures

Several methods of mixing enriched air are in use. The two main principles are mixing by partial pressure according to the gas laws (often called "cascading") and by mixing continuously with constant analysis and adjustment (the "NOAA" method; Mastro, 1989; Wells, 1989). The partial pressure methods differ according to whether the gas is mixed in storage tanks or directly into the scuba tanks.

The concerns here are getting clean air for the mix, making the proper mixture, compression of the mixture once it has been prepared, suitability of the storage and handling equipment for use with oxygen or oxygen-enriched mixtures, and analysis. In most cases the heart of the issue is exposure of compressed air and equipment to high-pressure oxygen. If at any time during a mixing or handling process the system is exposed to pure oxygen, even incidentally, then the system has to be **suitable for oxygen service.**
Callout Box:*"If you're gonna run with the big dogs you have to learn to pee in the tall weeds."* Gary Goodan, Lubrication Technology Inc. on standards.

The Workshop dissected these issues, recommending specific guidelines or standards where the matter is clear, defining needs for new information where that is needed, and calling for new specifications and equipment where proper ones do not now exist. Interim standards of practice are recommended until these needs can be met. The objective is, in due course, to make the entire process comply with standard industry practice.

Compressors and oil-free compressed air

The first issue in preparing an enriched air mixture is the matter of getting clean compressed air suitable for use with oxygen as the basic mixture. The ideal method is to use a properly maintained oil-free or oil-less compressor designated by the manufacturer for breathing air or enriched air service. The alternative method is to use an oil-lubricated compressor (suitable for breathing gas) and filter the gas prior to use. There is no doubt that correct filtration can clean up air sufficiently for use with oxygen; the problems are to ensure that the filtration system is adequate, to check is periodically, and to ensure that both compressor and filtration system are maintained properly. No adequate means was offered to ensure that this would always be done; hence, there was a strong feeling that using oil-free compressors is the only really acceptable method.

While it is technically possible to filter out the oil from the output of an oil-lubricated compressor, it is not clear how to specify when the air is clean enough for use with oxygen. **An important point is that the air that meets standard specifications for breathing gas such as those of the U.S. Navy, Compressed Gas Association (CGA) or the Occupational Safety and Health Administration (OSHA) may very likely not be clean enough for use in preparing enriched air.**

Oil levels tolerable for breathing (e.g., CGA grades D and E) can, in time, coat the inside of a gas system enough to cause a fire in the presence of oxygen (Mastro and Butler, 1990; NFPA 99, 1990). Although there are practical methods for maintaining oil-free air, existing commodity specifications for gases do not address this issue; these are generally each designed for a specify purpose, and none happens to be right for this application. Gaseous hydrocarbons like methane, in small quantities, are not a problem, but condensable hydrocarbons&endash;oil mist&endash;are a real problem, and some hydrocarbon tests of gas samples do not detect the oil mists. Proper sampling and analysis are needed for this to be detected. Existing specifications for gas sufficiently free of oil to be used with high-pressure oxygen call for levels of other components too low to be met with reasonable methods. A new commodity specification is needed for breathing air to be mixed with oxygen.

In the meantime, as a rule of thumb, compressed air to be used for mixing with oxygen in preparation of enriched air mixtures should leave no detectable oil residue in piping after several days of pumping. A clean swab after wiping the inside of the piping should show no discoloration and no glow under ultraviolet light (Mastro and Butler, 1990). Because of the subjective nature of the test methods, experienced gas mixers at the workshop stronger recommend the use of oil-free compressors. In particular, while properly maintained and filtered oil-lubricated compressors may be acceptable for "in-house" where rigorous maintenance and monitoring are practiced, enriched air offered for sale and the stations selling it should meet "oil-free" specifications.

This discussion focuses on oil, but other possible contaminants should, of course, be controlled at or below the limits for compressed breathing air. Compressed air pumped with any oil-lubricated compressor may contain abnormally high concentrations of carbon monoxide. Any compressor, oil-lubricated or not, could entrain CO in the intake stream. Existing standards and practice for monitoring and removing carbon monoxide from breathing air are adequate for use with enriched air, and they should be followed as a minimum.

Once the gas is mixed it may have to be compressed into the scuba tanks. In this application an oil-free or oil-less compressor or booster pump, or one compatible with oxygen, is essential. An oil-lubricated compressor is not acceptable for this use under any circumstances. The booster should meet manufacturer’s specifications&endash;or better&endash;for this application (that is, compressors suitable for oxygen service may be used for enriched air).

One easy way for a dive shop to avoid problems yet to be able to sell enriched air mixtures is to acquire premixed gas from an industrial gas supplier and to use an appropriate booster to pump it into scuba tanks.

One sticky aspect of all this is that compressor manufacturers maintain that compressors should be used only for the mixes specified, and there are few, if any, currently available for compressing enriched air. By way of background and to emphasize the scope of the problem, the most popular and cost-effective low-pressure air compressor used by the U.S. commercial diving industry is clearly labelled as not being suitable for breathing air.
It was pointed out that merely being "oil-free" may not make a compressor suitable for enriched air use. This is a matter for the manufacturer to determine on the basis of the nature of the gas being compressed. Opinion was further offered that many dive shops currently produce air or otherwise use practices that would not be compatible with oxygen-enriched mixtures.

Oxygen percentage and risk of fire

The requirements for safe handling of compressed air are well known and standards exist. Likewise, a complete technology exists for handling 100-percent oxygen. For the range in between, however, the situation is not clear, either in terms of "rules and regulations" or in the technology itself. The concern here is for gases at high pressures, above about 200 psi. It is well known that mixtures with oxygen in the range of air up to a composition of 40 or 50% are much easier to handle than oxygen, and for the most part can be handled with methods similar to those for air. In fact, several existing standards allow mixtures of up to 40% oxygen to be used in equipment designed for air service, or conversely, requiring mixtures having oxygen percentages above 40% to be handled with the same methods and equipment used in oxygen service. But because there are few engineering reasons to use mixes with oxygen in the enriched air range, few tests have been done and few, if any, standards developed.

The Workshop recommended that testing be performed to address the specific issue of using standard sport/recreational scuba tanks, valves, hoses, gauges and regulators with high-pressure mixes of oxygen and nitrogen. Because some enriched air scenarios may call for mixes with oxygen in the 40- to 50-percent range, mix compositions tested should be up to a level of 50% oxygen, and pressures up to 5,000 psi. Until such testing can be performed, the Workshop accepted interim recommendations. Because of the extensive experience in the use and handling of high-pressure mixtures in the range between air and 40-percent oxygen, the Workshop agreed that such mixtures can be handled safely in ordinary equipment provided that air quality requirements are met, that the mixture is completely mixed before coming in contact with any equipment not suitable for oxygen service, and that all lubricants used anywhere in the system be compatible with high-pressure oxygen.

Although the Workshop came up with these guidelines relating to handling of oxygen mixtures, it is recommended that anyone setting up an enriched air facility or any facility handling high-pressure oxygen consult with an oxygen expert. Again, the use of commercially made premixes is a suitable approach.

"Home brew" mixtures and mixing in scuba tanks

It should be noted that the preceding recommendations will preclude the current practice of filling a scuba tank to, day, 600 psi with oxygen and topping with compressed air. This is the so-called "home-brew" method of mixing. It can be highly dangerous, especially if the compressor is not oil free or properly filtered to provide truly oil-free air. If oxygen were to leak back into an oil-lubricated compressor, it could cause an explosion. Oil from the compressor combined with the oxygen in the tank could cause ignition of the lubricant or nonmetallic portions of the tank valve. This practice is especially dangerous if the compressor operator, usually a dive shop, is not aware that oxygen is being use (or how to handle oxygen). The Workshop recommended that this practice be stopped. This practice can be dangerous from the physiological perspective as well, since usually the diver does not know the exact composition of the mix and may therefore encounter oxygen toxicity or decompression problems. A warning should go out to dive shops advising them not to fill partially full cylinders unless they can be sure that the residual gas in the tank is not oxygen. If the gas in the tank cannot be checked, then it should be emptied before refilling.

Clalout box: *This Mixing On Elm Street stuff scares the bejezzus outa all of us."*
Michael Parker, Rix Industries.

While this mixing practice is not compatible with ordinary scuba gear, mixing in a tank with oil-free air can be performed safely *if the tank is equipped for oxygen service*. This means any lubricants have to be oxygen compatible, nonmetallic components shall be appropriate for oxygen service, and all components have to be cleaned for oxygen service. If there is a gauge on a hose, it shall have a snubber, so pressure takes at least one second to build up. Kits are available from the manufacturer for some regulators and valves to meet these requirements. Once cleaned for oxygen service, the tank and equipment shall be "**dedicated**" to enriched air use and so marked; if used with ordinary compressed air again, it shall be cleaned before being used again with oxygen.

The term "home brew" as used here is not intended to be critical of those technically trained and properly equipped divers who make mixes at home using proper techniques.

Lubricants and nonmetallic components

One area regarded as an "easy fix" is that of lubricants. **The lubricant in a high-pressure gas system containing oxygen is by far the most vulnerable and easily ignited part of the system, but it is also the most easily corrected.** Effective lubricants that will not burn in oxygen are available. The best of these are the perfluorinated polyethers. These are more expensive initially than silicones, but are well worth it in the long run. The Workshop recommended that perfluorinated polyether lubricants be used exclusively on diving apparatus. (These lubricants are for the valve, regulator, O-rings, etc., not for the crankcase of a compressor.)

There is a "myth" in parts of the recreational diving community that silicone greases are oxygen compatible, whereas in fact they are highly flammable in oxygen and can initiate fire in an oxygen system of incorrect design or with incorrect handling. The manufacturer states clearly that such lubricants are not to be used with oxygen.As mentioned, if a valve and regulator are to be used for mixing and may even incidentally be exposed to oxygen, in order to make them compatible with oxygen the nonmetallic components shall be made of oxygen-compatible materials. These should be available from the manufacturer.

Tank valves and connectors

The Workshop identified another area where the practice of putting enriched air mixtures in scuba tanks is not in compliance with current industry standards. This is the connector used for attaching the regulator to the tank valve. The Compressed Gas Association has identified proper connectors for most gases used in industry, medicine, etc. However, there is not a suitable connector for a scuba tank having an enriched air mixture between 23 and 50%. Although oxygen-compatible components in a gas system will work with mixtures lower in oxygen than 100%, an oxygen connector would not be suitable for use with enriched air.

The solution is to define a new unique connector for enriched air and work it through the "standards" process. The Workshop recommended that this be done. It was suggested that a DIN-type connector be designed (this may, however, require European involvement). It should be noted that implementing a new connector would go a long way toward ensuring "dedicated" service of enriched air equipment, as is recommended. This step is necessary in order for the practice of enriched air diving to be fully in compliance with standard industrial practice.

Tank and equipment corrosion

Another area about which there has been considerable misunderstanding and misconception is the question of corrosion of tanks and deterioration of equipment exposed to enriched air mixtures. Experts in the workshop laid this one to rest. There is **no noticeable difference** in corrosion between a tank containing dry air and one containing dry enriched air. The same applies to nonmetallic components; there is no difference.

Almost as if to provide a basis for this misconception, one organization using enriched air reported considerable tank corrosion and, in the case of aluminum tanks, formation of a jelly-like mass in the tank. This was diagnosed as being due to the compressor pumping water into the tanks, not as a result of the composition of the gas mix. The corrosive action of sea water in standard scuba tanks is well known. The recommendations are obvious: ensure that all water is removed from any gas compressed into tanks.

Mixing and analysis

Differences in style of analysis were presented, but this was regarded as a problem area only where analysis is not done at all. Some feel better using two different analyzers. others with considerable experience in gas analysis maintain that a single analyzer properly calibrated is satisfactory. Some mix by rolling, others by waiting, others with mechanical means. The main conclusion, however, on which there was universal agreement, is that all gas mixtures other than compressed air to be used for diving shall be analyzed before use. If the mix has just been made, it should be analyzed again later to ensure proper mixing. Mixing by pressure with no analysis is acceptable only if air decompression tables are used such that the actual composition does not matter, but the risk of oxygen toxicity may still remain.

Procedures not complete here

It is important to point out clearly that these comments and recommendations do not in any way comprise a complete "how to" manual for mixing and handling enriched air. They are recommendations of experts backed up by experienced users and are as up to date and correct as can be expected for the circumstances, but they are by no means complete. They should be used in conjunction with proper engineering expertise.

Likewise, not all issues have been cleared up. Some ideas were passed on to a working group for later action; these are listed at the end of this report.

Training, certification, control and accountability

A major issue leading into the workshop was that of training and certification of divers using enriched air, those instructing in it , and those dispensing it. There appears to be a lack of credibility. The established agencies dealing with the recreational diving community feel that enriched air has no place in that community. The recreational diving domain covers no-stop diving with air to depths not exceeding 130 fsw, and because of these boundaries is marketable to a wide constituency. The Workshop recognized the importance of that position, and did not challenge it or the philosophy behind it. But the Workshop did discuss and make recommendations on the issues of training, instruction, certification, and gas dispensing for enriched air diving.

Clearly there is a lack of understanding among the recreational community of what diving with enriched air entails. Many clearly group it with "technical" diving, unaware that the depth limit of useful enriched air diving (with 32% oxygen, NNI) is these same as that of recreational diving: 130 fsw. Others perceive that a great deal of specialized training is needed. This is not the case. If the problems of mixing and handling can be dealt with separately and the appropriate depth limit is clearly established, the enriched air diver needs to know only two things: (1) Breathe in, and (2) Breathe out. This somewhat tongue-in-cheek comment caught on and served as an example of the relatively little amount of in-water training needed, but the importance of understanding partial pressures, oxygen limits, and handling oxygen-enriched mixtures were not forgotten. One point about the necessary training for enriched air is that this transition is far, far easier than the initial one from being a surface air breather to breathing under water as a scuba diver. Any additional risk that may be imposed on a diver by enriched air becomes a trivial part of the total risk package.

Callout: If the problems of mixing and handling can be dealt with separately and the appropriate depth limit is clearly established, the enriched air diver needs to know only two things: (1) Breathe in, and (2) Breathe out.

One source of experience with enriched air is the scientific diving community. There, several programs are carefully controlled, highly successful in both productivity and safety, and enthusiastically received. These are not typical models for recreational diving, however, because they have organizational control of the operation, ongoing professional support, and the ability to treat for DCS and manage other accidents. There is an important message here.

Another model for self-regulation comes from the cave diving community. Several years ago an ongoing series of fatalities of divers in Florida caves and the threat that the whole practice would be shut down inspired cave diving enthusiasts to put their house in order. Two organizations interested in cave diving established training standards and in due course certified instructors and cave divers, with the result that this activity is now under good control.

The organizations are competitive, but they both meet a minimum agreed-upon standard and they jealously guard the domain of cave diving. Cave diving is recognized and considered credible by the traditional recreational agencies, and they are not threatened by it. Differences between this and enriched air diving are that the latter imposes no great threat, the consequences of lack of training are not recognized as being so severe, and there is no "access" control; it is not nearly so easy to separate enriched air from recreational diving as it is cave diving. It was mentioned that the problem is that there is no problem.

The issue of how enriched air training and certification is to be handled was discussed at length. Despite the perception that there was no credible agency for enriched air diving training and accountability (e.g., Bennett, 1991), the Workshop decided that the existing "agencies," provided that they adopt a uniform standard, can adequately meet this need. These are IAND, the International Association of Nitrox Divers, Key Largo, Florida, operated by Dick Rutkowski with Tom Mount, and ANDI, the American Nitrox Divers, Inc., Freeport, New York, operated by Ed Betts and Doug Pettit. Both are private, for-profit organizations (but then so is PADI). In accepting these agencies, the Workshop charged them with the task of producing and disseminating to other agencies a uniform standard for training and certifying divers, instructors, and dispensers of enriched air. The acceptance of these organizations does not preclude other new or existing agencies from becoming involved in the future.

Another issue could be called the "education gap" in current recreational diver training. One of the reasons why there is concern about recreational divers doing enriched air diving is that the level of understanding of the basic physics and physiology of diving is generally weak throughout the recreational diving community. It is recommended that these be brought up to speed for divers to be trained in enriched air.

Callout: One of the reasons why there is concern about recreational divers doing enriched air diving is that the level of understanding of the basic physics and physiology of diving is generally weak throughout the recreational diving community.

If adequately trained divers will insist on buying their gas from accredited dispensers, and if dispensers will only provide gas to accredited divers, the system will go a long way toward policing itself. This, obviously, is exactly the mechanism currently in place within the recreational diving community for normal scuba divers.

Liability and the manufacturers

The panel assembled for this section included lawyers specializing in recreational diving issues and representatives from several diving equipment manufacturers and training agencies. It is even more risky to try to summarize legal tactics than oxygen handling, but some points were made. Clearly the best way to avoid liability is to prevent accidents. Records of training are helpful. Releases may work when people are doing things by choice. Warnings work. The industry has to have uniform, recognized standards that are followed. Diving equipment is life support equipment for use in a hostile environment. Product liability is not based on fault, and negligence need not be shown; *caveat emptor* (let the buyer beware) is long gone from the American scene. A defense is to show no defects and keep quality high. "Free of defects" depends on the standard of care within the industry. Standards, if followed, also help. If there is no standard for the specific segment, then standards from other areas of technology can be invoked by the plaintiff; expect the worst when this happens. Designer, manufacturer and seller are all potentially liable, and a vessel may be as well; the plaintiff tries to get them fighting among themselves. One suggestion for a large organization doing enriched air is to incorporate the enriched air portion of the activity as a separate company, if that is regarded as especially risky.

Manufacturers offered a mandate: They want a good standard.

The DEMA warning was discussed. It was agreed that it was not well founded on correct facts. The legal opinion was offered that the warning statement would not be much help to the shop or manufacturer, and would probably help the plaintiff. A new warning is proposed, dealing with the limits for mixing and handling given above, and directed at the "home brew" practice.

One more point was made that would help as the process of acceptance and certification moves along. That is the recording of dive experience. Logs of dives should include, where possible the time-depth profile and should include the composition of the breathing gas. These should be made available to a central agency for storage and analysis, although no such agency presently exists.

Open issues and formation of a working group

In order to address future work the panel broke up into two small working groups, one addressing standards and the other engineering. Each produced a short report and listed certain "action items" that need attention.

Among the conclusions of the "standards" working group was a preamble saying that the group (speaking for the Workshop, but because of the lateness of the hour without full Workshop consensus) could see no valid reasons why enriched air diving could not safely be practiced in the recreational diving community, given compliance with a common industry standard (yet to be delineated) for training and certification, equipment, filling and handling of mixes, and operational limits. In addition to training and certification of divers, it is felt that instructors and particularly the "dispensers" of enriched air mixes also need training and certification. The existing system of "control" for recreational divers could serve for enriched air diving as well. Diving with enriched air should not be classed as "high-tech" or "technical" diving.
The list of needs prepared at the Workshop is given here; some redundancies exist. The "needs" of some items are described in more detail above in the text of this Workshop.

Action Items:

1. IAND and ANDI, as the existing air training organizations must cooperate, together and with others interested recreational training agencies, in establishing a common industry standard for filling (mixing and handling) training, certification, and diving with enriched air.

2. Encourage accurate and centralized collection and recording of enriched air dives to include as a minimum details on mixes and time-depth profiles, decompression sickness, and other incidents or accidents.
3. Define a commodity specification for gas mixtures used in enriched air diving.
4. Provide to scuba equipment manufacturers information regarding the present status and future prospects of enriched air diving.
5. Develop a unique connector suitable for scuba tanks used with oxygen enriched air mixtures.
6. Perform testing of specific scuba equipment with enriched air mixtures.
7. Encourage the close review and appropriate testing of the fire and flammability behavior of mixtures of nitrogen and 40% and 50% oxygen, to establish material, lubricant, and cleaning requirements.
8. Quantitatively define acceptable levels of contaminants for air used in making enriched air mixtures.
9. Rewrite the DEMA notice to the diving community regarding enriched air to ensure correctness and appropriate safeguards.
10. Publish a consensus statement of this meeting, action items, and a proceedings.

The Workshop formed an *ad hoc* working group to address the main open issues. The following list of items were discussed and action was promised. The auspices of the committee are at the moment unclear, but the members are eager to address the open issues, and when ready, to prepare proper standards. People not named to the group but interested in participating are encouraged to volunteer.

Engineering Working Group Agenda

Assignments of the Engineering Working Group for Enriched Air Nitrox included the following:

1. Identify compressors compatible with air mixtures.
2. Do a search for federal regulations and specifications for diving standards and historical documents applicable to enriched air mix preparation and handling.
3. Do a search for industrial specifications, diving standards, and historical documents applicable to enriched air mix preparation and handling.
4. Prepare an inventory of industrial documents related to nonmetallic materials to be used in contact with enriched air.
6. Prepare an inventory of industrial documents related to metallic materials to be used in contact with enriched air.
7. Identify or develop a commodity specification for oxygen enriched air breathing gases.
8. Review filtration requirements for oil-lubricated compressors for possible use in enriched air mixing.
9. Identify requirements for a dedicated high-pressure connector system for scuba tanks to be used with enriched air.
10. Identify the areas in which testing with enriched air will be required.

Dr. R.W. Bill Hamiton is a diving physiologist and principal of Hamilton Research Ltd. with over twenty years of decompression management experience in the hyperbaric and aerospace industries. He can be contacted at 80 Grove St., Tarrytown, NY 10591. Fax: 914-631-6134.
Copies of the original report which include an abstract and a participants list can be purchased for $10 from the Scuba Diving Resource Group c/o Outdoor Recreational Coalition of America, PO Box 3229, Boulder, CO 80307 .