NATIONAL UNDERSEA RESEARCH PROGRAM Research Report 89-1

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Workshop on Enriched Air Nitrox Diving

R. W. Hamilton, Dudley J. Crosson,
and Alan W. Hulbert, Editors

September 1989

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This Research Report contains the papers presented at the Harbor Branch Oceanographic Institution/NURP workshop held February 11-12, 1988, in Fort Pierce, FL. This workshop was organized to discuss and review the pertinent physiology and special technology of enriched air nitrox diving and its applications to the scientific diving community. In addition to the papers, the resulting discussions have been included. Participants represented academia, government, and private industries.

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FOREWORD

The National Oceanic and Atmospheric Administration (NOAA) has the largest diving complement of any civilian Federal agency. Under the aegis of NOAA's Undersea Research Program (NURP), the agency also directly assists a large cadre of marine research scientists to conduct their scientific activities under the sea. This research is accomplished using manned submersibles, remotely operated vehicles, and compressed-air scuba, mixed-gas, and saturation mode diving. Additionally, the NURP assists all divers of the nation through research undertaken in accordance with the terms of Sec. 21(e) of the Outer Continental Shelf Lands Act of 1978 (PL 95-372; 43 USC 1331 et seq.). This statute requires NOAA, under the authority delegated by the Secretary of Commerce, to "... conduct studies of underwater diving techniques and equipment suitable for protection of human safety and improvement of diver performance. Such studies shall include, but need not be limited to, decompression and excursion table development and improvements and all aspects of diver physiological restraints and protective gear for exposure to hostile environments."

The Research Report series published by NURP is intended to provide the marine community with results of undersea research, often presented at NURP-sponsored symposia and workshops, in a timely fashion. In the majority of instances, participants at symposia or workshops are reporting on results of NURP-sponsored research. In such instances, the printing of their papers meets report requirements of grantees to the Office of Undersea Research.

On February 11-12, 1988, a workshop jointly sponsored by NURP and the Harbor Branch Oceanographic Institution (HBOI) in Fort Pierce, Florida, was organized to discuss and review the pertinent physiology and special technology of enriched air nitrox diving and its applications to the scientific diving community. Papers presented at HBOI together with resulting discussions have been assembled, edited, and submitted to NURP as camera-ready copy in partial fulfillment of requirements under award # 40AANC800603. It is printed in its entirety as presented.

Comments on the report are welcome. They should be directed to:

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Rockville, Maryland
September 1989

David B. Duane
Director

PREFACE

The Office of Undersea Research, NOAA, U.S. Department of Commerce (NURP) conducts research and exploration on the continental shelves and slopes. NOAA's Diving Office has been instrumental in developing a unique diving method in support of scientific diving. This Workshop was convened for the purpose of bringing institutions with scientific diving programs who were interested in enriched air or nitrogen-oxygen--"nitrox"--diving techniques together with those having experience in the technology, including other scientific diving organizations, commercial firms, diving physiologists, people with operational experience, and others with appropriate experience or expertise.

The technique consists of making dives breathing gas mixtures having a larger fraction of oxygen than is found in normal air. This technique is most effective in the middle part of the air diving depth range; it can offer a considerable reduction in decompression obligation and at the same time improve the decompression reliability.

While there are several clear cut operational methods for using gas mixtures consisting of oxygen and nitrogen with a larger fraction of oxygen than is normally found in atmospheric air, it is not quite so clear what to call it. Since these gas mixes are almost always made by adding oxygen to air, one suggested and often used term for both the mix and the process is "enriched air." Since the gas mixtures are composed of nitrogen and oxygen they are often called "nitrogen-oxygen" mixtures, or simply "nitrox," but this term "nitrox" is also used to refer to nitrogen-oxygen mixtures having less oxygen than air, such as might be used for the atmosphere of an undersea habitat. All these uses, including the jargon, are technically correct and acceptable, and there was no obvious choice of how to reference it in this Workshop. Accordingly, the Workshop's participants use the terms "enriched air" and "nitrox" or "nitrogen-oxygen" interchangeably. We suggest for more formal use the non-ambiguous term, **"enriched air nitrox."**

The Workshop was sponsored by NURP and Harbor Branch Oceanographic Institution. We thank our sponsors for their support. We also thank all who helped, especially Steve Blair and Yvonne Robertson at Harbor Branch for their organizational assistance, Andy Shepard and the staff of the NOAA Undersea Research Center at UNCW for the production of the original manuscripts and initial editing, Eileen Whitney of HRL who did the formatting, and NOAA's Office of Undersea Research who did the printing. The text was formatted with WordPerfect 5.0 and printed on an HP Laserjet II, with the predominant type face Bitstream Dutch 11 pt.

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Chapter I. Abstract

ABSTRACT

Hamilton RW, Crosson DJ, Hulbert AW, eds. 1989. Harbor Branch Workshop on enriched air nitrox diving. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

The objective of this workshop was to review the pertinent physiology and special technology of enriched air nitrox diving and its applications to the scientific diving community. Current scientific diving in the US is predominately done in closely controlled programs, uses scuba equipment, and where practical tries to avoid the need for decompression stops. "Enriched air" or "nitrox" is a mixture of air and oxygen; the oxygen component ranges to about 50% but is used normally at 32 to 40%. One specific mix at 32% O_2, balance N_2, is called "NOAA Nitrox I" and has been used extensively in well established scientific diving programs; commercial operations mostly in the 32 to 40% O_2 range have logged thousands of trouble-free dives. Enriched air diving is bounded primarily by the potential for oxygen toxicity, decompression, and the necessity to handle oxygen-enriched gases. The practical depth range is 15 to 40 metres of sea water (50-130 fsw). There is general agreement that because of CNS toxicity the PO_2 should not exceed 1.6 bars (1.6 atm) and is time limited at that level. Slower acting O_2 toxicity can be managed by a new multi-day approach that replaces the traditional US Navy limits. Substantial evidence supports the validity of the "equivalent air depth" method of calculating decompression, which uses reliable air tables having the same PN_2 as the nitrox mix in use. For no-stop diving the USN Standard Air tables are considered reliable in this application. Other methods use fixed mixes and predetermined tables (NOAA Manual), or custom calculations which offer some additional efficiency; there is currently no dive computer for nitrox. Methods of mixing include gas-law pressure mixing into tanks or banks followed by replicated analyses, or on-line mixing by blending O_2 into the intake of an oil-free compressor. Scuba tanks should be dedicated and properly labelled, and use of dedicated, oxygen-clean first-stage regulators is recommended. Closed and semi-closed diver-worn rebreathers offer another useful approach to enriched air diving. This Workshop did not address recreational diving with nitrox and specifically did not recommend it, but acknowledged that it is happening anyway. Safe enriched air nitrox diving practices established for the scientific diving community might be of some value and could help avoid accidents due to ignorance of its hazards and use of improper procedures.

Chapter II. Welcome

WELCOME

Jay Langfelder, Vice-President & Managing Director
Harbor Branch Oceanographic Institution

I have two tasks. First is to recognize the quality of the group. It seems to me that we have the cream of the crop in diving here today.

The second thing is to welcome you to Harbor Branch. Some of you have had a long history and association with Harbor Branch, going back to its inception. Harbor Branch is about seventeen years old; I have only been here two years.

When I started it occurred to me that even though our organization is young, it nevertheless has a tremendous history of interaction with a whole variety of people. I am extremely pleased to have Dudley Crosson on board now. He is our safety officer and is experienced in not only industrial safety but other aspects as well. We take diving safety and other safety very seriously, and we are pleased to have a highly trained individual to look over it.

I hope you have a chance to view the campus while you are here. Our submarines are torn apart as they are every year at this time, but *R/V SEWARD JOHNSON* is in and *R/V SEA DIVER* is in. You will have a chance to see them.

I hope you have a productive workshop.

Chapter II. Invited speakers.

ENRICHED AIR DIVING AS APPLIED TO SCIENTIFIC SUPPORT

Dudley J. Crosson, Ph.D.
Harbor Branch Oceanographic Institution
Fort Pierce, Florida

Dr. Crosson had the dual role of diving officer and safety officer at Harbor Branch, and he was tasked with reviving diving as a tool for Harbor Branch scientists after a period of a few years when it had had relatively low emphasis. He had used "nitrox" or enriched air diving techniques at Florida Institute of Technology, and in planning for the future introduction of this diving method at HBOI he recognized the need to survey the current state of the art in nitrox diving. Hence this Workshop. Dr. Crosson is presently an independent consultant.

ABSTRACT

Crosson DJ. 1989. Enriched air diving as applied to scientific support. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

As scientific diving faces more demanding operations the field is beginning to incorporate new technologies. A strong tradition backed up by a good safety record has kept scientific divers into a rather narrow envelope of air diving with scuba; very few dives involve decompression stops. Now interest in at least one new technique, enriched air nitrox diving is beginning to mount. Other users that serve as an example include the NOAA diving program, miliary operations, and commercial companies; some scientific diving institutions are beginning nitrox programs, and a set of standards have been issued by the American Academy of Underwater Sciences. Concerns are safety and cost effectiveness, and both seem to be improved if nitrox is used properly. Decompression from enriched air diving depends on the "equivalent air depth" principle, but there are also both prepared tables and "custom" decompression procedures. Problems include mixing methods as well as decompression, but "control" is the main concern, initially to regulate well controlled institutions but also to avoid fallout from improper use that may lead to accidents and incidents in the relatively unregulated sport diving community.

INTRODUCTION

There is a growth phase currently taking place within the scientific diving community. This growth is due to two aspects, more demanding operations and current technology. Operations are becoming more and more expensive so alternatives are imperative in order to meet the research challenges. Investigation into diving alternatives is nearly rivaling that of the commercial diving industry fifteen years ago. The scientific diving community does, however, have the advantage of reviewing what has taken place earlier in order to avoid similar mistakes. The technology available to the scientists could promote the necessary growth by leaps and bounds. In twelve years, we will enter the year 2000: the time seems appropriate for scientific living to emerge out of the current antiquated level of operation.

ENRICHED AIR AS A SCIENTIFIC TOOL

It does appear appropriate, at this time in the growth phase, to take a hard, in-depth look at what enriched air nitrox can provide for the scientific diving community. This is exactly the intent of this workshop, to bring together not only organizations that are currently utilizing nitrox, but those that are seriously considering its use. In essence, to share information on operations, physiology, table considerations, etc.

As will be seen in this workshop, enriched air diving is not new by any means. From my review of past operations and literature, it just has not enjoyed a rapid growth for whatever reason. It appears that its time has come; time for a renewed interest.

Organizations that have used nitrox vary, but the common bond is the need for more bottom time while providing a safe diving operation. The group of users includes governmental such as the NOAA Diving Program and NURP, military such as the U.S. Navy, commercial such as International Underwater Contractors (Butler et al, 1984), Oceaneering International, and Comex, and scientific such as the Florida Institute of Technology (Crosson, 1986; 1987) and the University of Miami. Along with these, I have been contacted by several organizations expressing an interest, including the University of Florida, Florida State, the U.S. Army, the Smithsonian Institute, etc. Enriched air diving standards have been adopted by the American Academy of Underwater Sciences in order to facilitate its use.

While entertaining questions regarding the use of nitrox, there appears to be two areas of significant concern to potential users, safety and cost benefits. There is no doubt that safety is of paramount importance to all of us. It will be seen in this workshop that there are a number of safety advantages nitrox has over air, including richer oxygen contents, lowered nitrogen narcosis, less decompression commitments, etc. As far as cost benefits is concerned, the author has observed significant cost savings on ship use time. For example, if a diving operation can provide the same amount of bottom time for data collection in four days rather than six or seven, ship costs are lowered (Crosson, 1986; 1987). This would allow more funding for data analysis. The cost benefits issue is an interesting change from the concept many people have regarding science; grants are not bottomless. As the commercial companies have an interest in more bottom time in order to lower operating cost which provides more profit, scientists would like more bottom in order to lower operating costs to stretch their limited funds.

As mentioned earlier, scientific diving is in an era that is quite similar to the commercial industry approximately fifteen years ago. The need for alternatives in diving is apparent in order to provide deeper diving, extended bottom times, safer operations, etc. This is the reason for various scientific diving programs such as the University of North Carolina, Woods Hole Oceanographic Institution, Florida State University, etc. to utilize surface supplied diving to meet certain needs. Enriched air in conjunction with surface supplied diving would add that much more to the safety of the diver. There is a growing interest in the use of closed circuit diving systems; again, nitrox provides an added benefit. Here at the Harbor Branch Oceanographic Institution (HBOI), we are currently building towards a program which provides many alternatives for the scientists including scuba, surface supplied, and closed circuit systems in conjunction with enriched air and heliox mixtures.

OPERATIONAL ADVANTAGES

It is the intent of many scientific organizations to allow only no-stop (or "no-decompression") diving. There is nothing wrong with this providing it is done properly. It is much safer for a diver to stop and decompress than to push the no-stop limits. This is where enriched air nitrox provides an excellent alternative. It allows the diver to lengthen his/her bottom time, but still remain in a no-stop situation.

The option of using the equivalent air depth (EAD) method or limiting the operation to one or two mixes must be reviewed (Berghage and McCracken, 1979; Logan, 1961). As in most areas, there are advantages and disadvantages to both. Obviously, if one wants to provide the most flexible of operations, "custom blending" is the answer. However, this requires more calculations and organizational skills. In situations where the Diving Safety Control Board may choose to limit the flexibility in order to reduce complexity, following the NOAA Nitrox I and soon-to-be II procedures would be the solution. Either way, an alternative has been provided. Another advantage to the EAD is being able to utilize the accepted tables of the Diving Safety Control Board. Discussions in which tables are to be used for any operation commonly provides for entertainment, or frustration depending on your role. The EAD option would allow one to utilize the nitrox in conjunction with the accepted tables with no problem. Again, here at the HBOI, we are developing a pilot program in order to demonstrate to the scientists the advantages of the use. In the past while I was employed at the Florida Institute of Technology's Underwater Technology Division, the practice was the use of the EAD with the Defense and Civil Institute of Environmental Medicine (DCIEM) tables.

PROBLEMS IN INTRODUCING ENRICHED AIR NITROX

To recall an old phrase, change creates conflict. As with anything, it can be frustrating to discuss new concepts with "old thinkers." The idea that anything other than air is probably unsafe is quite common with many of the Diving Safety Control Boards that the author has dealt with. When scuba air is the only diving that individuals have known, introducing enriched air provides for some interesting conversations. As a physiologist, I have attempted to explain the physiological benefits to safety for the diver. This tends to get peoples' attention, but the idea still prevails that if it is anything other than air, it must be costly and dangerous. Again, as a physiologist, my frustration grows while trying to explain why in many cases enriched air is safer than air. It is at this time that I sometimes feels like I have just insulted someone's mother. When discussing the concept of enriched air diving, the old horror stories of oxygen toxicity rise up.

In essence, one must be prepared to provide a thorough explanation from all aspects, including operational and physiological.

At this time, the issue of who should be using enriched air needs to be addressed. As is evident from this paper, I feel strongly about control. The Diving Safety Control Board is responsible for decisions. Then, the Diving Officer is in control of the on-site operation. Control is the key. This point alone stresses the fact that nitrox diving has no place in the sport diving community. There are two main issues that I feel support this view. First, control of the operation is essential; there is no control board for sport divers to answer to. Second, with this lack of control, should an accident occur (accidents have already occurred due to improper use of nitrox by sport divers) the emphasis of the accident would be placed on the nitrox, not the lack of control. Therefore this looms as a probable cause for the discontinuation of the use of nitrox for scientific purposes. It would be the inevitable "axe waiting to fall" concept.

THE FUTURE OF ENRICHED AIR NITROX DIVING

The two areas that I feel need to be stressed in the future are education and technology. The formalization, if you will, of a training program would provide standardization of training. Along with this, a formal training program could provide for a greater number of individuals introduced to nitrox.

Technological growth is everywhere, in every field. The use of computers is spreading into areas never dreamed of before. With the advent of dive computers and the eventual building of confidence in such units, it would appear that a logical outgrowth would be the development of dive computers for the use of nitrox. This could provide for either one fixed mix, or the EAD concept, depending on the expertise.

SUMMARY

There is no doubt that enriched air diving has proven itself as a viable alternative for safer diving. With the number of organizations currently using nitrox, the safety record will continue to grow. The only accidents that I have heard of in the past approximately four years have been those of sport divers who follow no founded guidelines. It is my hope that this workshop will, for the first time, provide a forum for the sharing of information and experiences in order to provide a catalyst for the growth of enriched air diving.

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Logan JA. 1961. An evaluation of the equivalent air depth. NEDU Rept 1-61. Washington: USN Experimental Diving Unit.

Additional Comments by Dr. Crosson:

Let me give you a little background on the Workshop and how it came about. I have had phone calls from individuals--such as, universities, various types of research companies, etc.--asking for training or for material on nitrox or enriched air diving. Certainly one can share only as much information as one has; I would make calls to people, some of whom are here, trying to get information. A lot of the attendees are here to gain ammunition because they want to present supporting material to their diving control boards. They want to get an active nitrox program going. So the material presented here will be used to enforce or reenforce their arguments.

When we looked at the literature we found there really is not a lot available on enriched air nitrox diving. There is a lot on table computation, but when you look at operational or physiological concerns there is not a whole lot out there. There are a few papers on the EAD theory. Bill Hamilton, Andre Galerne, and Glenn Butler have done papers on the use of enriched air in the commercial diving industry, but there is not much else there. So I felt it would be worthwhile to gather the big names if you will, and to share the information so that we could produce a printed proceedings of useful reference material.

Discussion Following Dr. Crosson:

DAVID A. DINSMORE: What is the applicability of nitrox as you see it in the future for sports diving?

DUDLEY CROSSON: This issue reflects my paranoia. Basically I think it deals with control.

With regard to scientific diving, with a diving control board in the university you have somebody to watch over you. You have a big brother to make sure that you know what you are doing. In sport diving it is a tough issue, because even though as a physiologist I know that this is safer than air if done properly, there is no controlling mechanism, there are no standards. So if we look at a sport diver who has been through training such as a PADI certification or whatever, even if it included nitrox diving, what is this guy going to do when he gets out there? Where is the controlling mechanism? There is none. That is where I get very nervous.

DICK RUTKOWSKI: I would like to talk on behalf of the sports divers sometime in the next day and a half. I am beginning a program with the sports community; I think it will be of interest to this group. I just came from the DEMA (Diving and Equipment Manufacturers Association) show and I passed out some literature and mentioned my program. You should have seen the number of people that told me that they were already using nitrox.

After talking to some of these people and seeing how they are mixing gases and how they are diving and how they got their information, I think we better not leave the sports diver out of this program today. I think we had better take note that they are out there and that they are doing it. They are doing it a lot of crazy ways. Anything we can do here as part of this program to ensure proper training to them I think should be brought up.

AN ANALYTICAL LOOK AT ENRICHED AIR DIVING

R.W. Hamilton
Hamilton Research Ltd., Tarrytown, NY 10591-4138

Dr. Hamilton has experience in developing decompression tables for all types of diving, including the nitrox and enriched air methods of this Workshop. In particular he has experience with the evaluation and use of different types of decompression tables, and decompression tables are the infrastructure on which nitrox diving is based. He works as an independent investigator through his company Hamilton Research, Ltd.

ABSTRACT

Hamilton RW. 1989. An analytical look at enriched air diving. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

Some distinct advantages, mostly related to decompression, can be achieved in diving in the range of about 18 to 35 msw (60-120 fsw) by using breathing gas mixtures containing a larger fraction of oxygen than air (normally 32 to 50% oxygen). Enriched air--also called nitrox--diving techniques use decompression tables derived for specific mixes such as NOAA Nitrox I (32% O_2, 68% N_2) or may determine decompression from a standard air table using the "equivalent air depth." The EAD principle considers that decompression depends on the PN_2 only; this has been shown to be as reliable as the air table on which it is based. Tables calculated on a custom basis offer advantages for some situations. One problem of enriched air diving is in dealing with oxygen, which may cause CNS toxicity at higher PO_2's and a whole body or "somatic" toxicity (primarily in the lungs) in multiday exposures. Both can be avoided by appropriate limitations, remaining within the established USN time limits when in the PO_2 range of 1.5 to 1.6 atm, and limiting the total exposure according to an empirical table based on OTU (or CPTD; accumulated oxygen toxicity units: 1 unit is about 1 min at a PO_2 of 1 atm) in longer exposures to lower levels of hyperoxia. For some "enriched air" dives the use of helium as the inert gas should be considered; there is no special thermal problem with helium as long as it is not used to fill a dry suit.

EDITOR'S NOTE: At the suggestion of Dr. Lambertsen in the discussion following Dr. Clark's paper, the term "chronic" which was used in the original presentation has been changed to "whole body" and/or "somatic." The term "chronic pulmonary oxygen toxicity" has a pathological and irreversible connotation that is totally unrelated to the pulmonary toxicity encountered in diving and would be both incorrect and misleading as it was originally used.

INTRODUCTION AND OBJECTIVES

A respectable body of experience has built up on the use of air as a breathing gas for diving, but the problems of diving with this gas are by no means all solved. Some considerable operational advantages (and some problems) can be gained by the use of mixtures of oxygen and nitrogen that have a larger fraction of oxygen than the 0.2093 normally found in atmospheric air. These advantages are mainly in the area of reduced decompression obligation, but there are some other small advantages; there are some disadvantages and limitations also. This paper is a review of the principles involved in enriched air diving and some thoughts on its operational applications.

These mixtures are usually made by adding oxygen to air, hence are properly called "**enriched air**" or "oxygen-enriched air" mixtures, but the name "**nitrox**" is also in use. The term "nitrox," however, is also used to describe the mixtures used in undersea habitats and saturation diving chambers where the fraction of oxygen is **less** than that of air. This paper is concerned only with the non-saturation uses of nitrogen-oxygen mixtures, so sticks with the terms "enriched air" or "enriched air nitrox." Personally I feel than "enriched air" is not only more correct, it may sound less intimidating to uninformed divers and to management concerned about diving operations.

The main advantage of increased oxygen is a reduction in necessary decompression. There are several aspects to this, depending on how the new decompression limits are determined. The extra oxygen may provide a small safety margin by postponing hypoxia in gas-related emergencies. The extra oxygen is also believed by some to lead to a slight reduction of narcosis that may in some cases be operationally helpful (oxygen itself is narcotic, however). There is a special set of problems with the use of higher levels of oxygen, and good procedures are required to deal with them; we offer here a new approach to the management of oxygen exposure.

A major factor to most divers using enriched air nitrox is the mechanical aspect of obtaining the **mixture.** This has a big impact on where and how enriched air diving can be done, and although the mechanics of mixing are not addressed here specifically, it is a matter of concern because it influences the choice of the **inert gas.** The topic of the workshop is nitrogen-oxygen diving, but for certain operational situations **helium** may provide a more attractive option; the mention of helium raises the question of thermal effects, but this problem is more apparent than real.

DECOMPRESSION ADVANTAGES OF ENRICHED AIR AND THE EAD

The theme of this workshop is that enriched air has operational advantages in comparison with air alone, primarily by improving decompression. This advantage may be implemented in several ways, all based on the principle that only the nitrogen component of a gas mixture--the PN_2 or nitrogen partial pressure--is involved in the requirement for decompression. There are two issues here, the **validity of the physiological principles** involved and the **means of implementing** them. A good case can be made that the decompression limits are for practical purposes determined only by the PN_2. There are three general methods for determining the decompression of an enriched air mix. One widely used method is based on the using standard tables at the "equivalent air depth." Others use special decompression tables made for a specific gas mix, or "custom" decompression tables which can be optimized for a variety of mixes.

This section addresses first the validity question through the EAD or equivalent air depth approach, the next section mentions the operational considerations of the different implementations.

The EAD or equivalent air depth

The **equivalent air depth** or **EAD** method involves use of an enriched air mixture with the standard air tables for determining decompression. In practice the nitrogen partial pressure of the enriched air mix is calculated and the air table having the same nitrogen partial pressure is used for decompression.

There seems to be little doubt that the EAD principle **works**, although some skepticism is still present (Dr. R.D. Vann addresses this in much greater detail elsewhere in the Workshop). One reason why there could be suspicion about the EAD method is that it results in a decompression obligation that may be substantially less than if air were used. In fact, there are two specific reasons why the EAD decompression may be <u>better</u> than a dive with air at the same PN_2 despite the fact that it is a shorter decompression. One has to do with the overall nitrogen load, the other with the gas breathed during decompression.

Exposure to lower inert gas levels

First, there is an observation that longer and deeper air dives require more than proportionally longer decompressions. This has been referred to as "duration of exposure to supersaturation" (Hamilton et al, 1980) and "the time-delta p integral," (Peterson and Greene, 1976) and was the impetus for Thalmann (1985) at NEDU to develop the new exponential-linear model for calculating tables. The conclusion is that excess gas loadings require more decompression than would be expected when using the unmodified Haldane method of calculation.

The converse of this seems to be true as well, that a dive with lower inert gas loadings should result in more reliable decompressions. Stated another way, it is widely held that oxygen seems to provide a benefit in a decompression beyond what can be accounted for by its replacement of inert gas. These agree with the idea that when some of the inert gas is replaced with oxygen, the decompression can be based on the **inert gas only**.

Thus we end up with a general apothem that decompression using the EAD is valid, and the decompression may be more reliable when the gas is changed to one of **higher** oxygen level than the air table used.

The other factor working in favor of the EAD is that the calculation deals only with the bottom mix, but the decompression--where stops are required--is presumably done using the oxygen-enriched mix as well. This of course is beneficial, and since it is generally not taken into account in the EAD calculations it acts as an added measure of conservatism. This effect is not significant with no-stop decompression.

Look at the data

It would be naive to base an operational procedure on technological assumptions alone if there are relevant data.

One paper by Berghage and McCracken (1979) based on experiments with rats purports to conclude that the EAD is not valid, but if one eliminates the data points where oxygen levels greater than about 2.0 atm are used the results support the EAD; levels of PO_2 above 2.0 are not operationally relevant except for treatment, and the physiological effects of oxygen, on circulation for example, at greater than about 2 atm are significant.

Dr. Vann will cover a carefully done comparative laboratory study comparing equivalent air dives with equal PN_2 dives done with air (Weathersby et al, 1986). In addition, there is experience with thousands of equivalent air dives that do not appear to have any more DCS than similar air dives. The impression of the users is consistent with the analysis just given. While this latter data base does not constitute a valid "clinical trial," it would very likely show up any serious flaw in the argument.

Validity of the air table

One thing to bear in mind in evaluating EAD diving, even with the benefits just mentioned, is that the EAD decompression may not be reliable if the air table on which it is based is inadequate. This is an important factor and one to be given due consideration. For example, the USN Standard Air Tables are reliable in the short and shallow range, but when decompressions get long--whether from a long bottom time or deep bottom depth or both--that reliability begins to diminish.

For typical scientific diving which uses little or no decompression (actually, few or no decompression stops; there is always some decompression), there is little question about the reliability of the air tables. In any case my recommendation in this range is to make a stop of at least 2 or 3 minutes at 10-20 fsw on all dives, especially the longer and deeper no-stop dives, whether using enriched air or not.

The 1983 DCIEM tables (Dept. Natl. Defense Canada, 1986) are likely to be more reliable in the range involving short decompression stops, and could quite readily be used with EAD calculations.

OPTIMIZING ENRICHED AIR NITROX DIVING

Once we accept the principle that decompression is based on the PN_2, the next question is to look at the methods of determining the decompression to use. As mentioned, there are three general approaches. One that is established and has an official look to it is the "NOAA Nitrox I" mixture and tables. These are given in the second edition of the NOAA Diving Manual; these tables were derived from the U.S. Navy Standard Air tables. This method has the advantage of being definitive, but the mix may not be the "optimal" one for a particular depth.

To look at optimization, specifically optimizing decompression in enriched air diving, consider Figure 1. This is a plot of gas mixes against depth and PO_2. The diagonal lines are different mixes, from the lowest one which is air, up to a 50-50 mixture as the upper one; the useful zone for enriched air diving is between these two lines. The heavy horizontal line is 1.4 atm PO_2, a possible upper physiological limit for oxygen exposure, but for shorter exposures PO_2's of up to as much as 1.6 atm may be used by some divers--more about oxygen later.

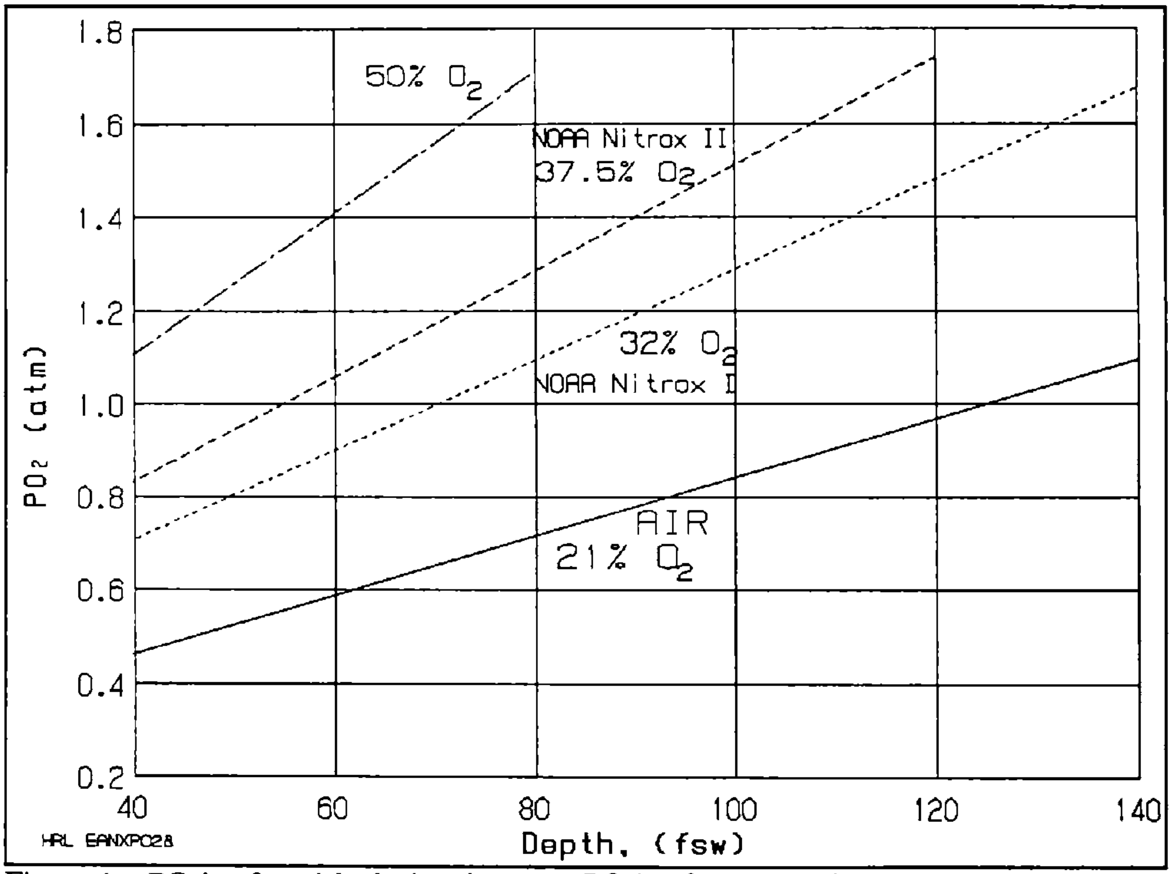

Figure 1. PO_2's of enriched air mixtures. PO_2's of several mixtures are shown for the effective depth range of enriched air diving.

At 120 fsw one might be able to use a mixture of 32% O_2 with a PO_2 of 1.5 atm. This is a 50% increase in oxygen fraction, but it is only about a 14% decrease in nitrogen fraction. This depth is 4.636 atm abs, and 68% of this is 3.15 atm PN_2, which is the equivalent to an air dive at 99 fsw. The no-stop time at 120 fsw with this mix is thus equivalent to the no-stop time for air at 100 fsw, or 25 min. This is also the no-stop time for 120 fsw given by the NOAA Nitrox I tables. At 60 fsw where one can use 50% O_2-N_2 the decrease in N_2 fraction is 37% and the equivalent air depth is 26 fsw. The no-stop time goes from one hour for air to essentially unlimited for enriched air.

Where times such as these are obtained from tables, because of the groupings the gains might be less than they could be if calculated directly, but it adds conservatism to the method.

To optimize, the **highest O_2 fraction** that can be used at a given target depth should be chosen for the appropriate maximum PO_2 to be used. For maximum benefit tables calculated for the intermediate values will allow a little more time, but will lose some of the extra J-factor (conservatism) that results from the groupings. The efficiency of these methods depends on how the mixes and depths fall into the tables (i.e., how they are grouped). Since the next deeper or next longer table is used there may be more conservatism than is needed. Repetitive dives can be calculated using the standard residual nitrogen groups.

Still another method for optimization is to calculate "custom" tables for the exact depth for the exact mix using a computational algorithm that is sufficiently conservative when used at face value. This capability is not yet available for enriched air nitrox mixtures in the diver-carried dive computers, but it can readily be done in the laboratory or at the dive site using a portable computer. Repetitive dives can be calculated for the exact history.

Thus to summarize the choices, using the NOAA Nitrox I tables the advantage is greatest near the deeper end of that gas's useful range, but at any depth this choice offers predetermined and established tables, which include repetitive procedures. The equivalent air depth gives one the option of selecting an enriched air mix that gives a higher oxygen fraction for shallower depths; this results in longer no-stop times, but at the expense of having to make calculations in order to pick the table. Custom computations are not easy to implement but give the most optimal profiles.

OXYGEN, THE PRINCESS OF GASES

The Swiss deep diving pioneer Hannes Keller has called oxygen the "Princess of Gases." She is beautiful, but she has to be handled with special care. This is certainly true to the diving physiologist, since inspired levels of this gas alone have both **high** and **low limits** compatible with life and health. Further, handling compressed oxygen requires special care, and although not of concern here, its excess in a human-occupied hyperbaric chamber can create a serious fire hazard.

Handling oxygen

Since the idea of enriched air diving is to make and use mixes containing higher oxygen than air, it is necessary to handle compressed oxygen. This is an item in the "cost" column of the enriched air balance sheet, but because the engineering and procedural aspects of oxygen management are well established and well known to the diving community, we need only to note that it is a consideration.

Hypoxia

Another oxygen problem, **hypoxia** or a low oxygen level, is relatively rare in air diving (although it is a major safety hazard in saturation and mixed-gas diving). Mixes used for enriched air diving begin with air, and the method normally does not involve the use of any gases with inadequate oxygen levels, at no matter what pressure they are breathed within the diving scenario. The higher oxygen levels used in enriched air diving in fact act as a benefit in potentially allowing longer breathholding and endurance in the event of loss of breathing gas supply.

Managing oxygen toxicity

The **toxicity** of oxygen is another matter. Both types of oxygen toxicity can be of concern with enriched air diving, but both can be managed. The types of toxicity, familiar to this audience, are a **central nervous system** (CNS) effect that usually results from a relatively short duration exposure to relatively high partial pressures of oxygen, and a whole-body or **"somatic" toxicity** that follows longer exposures to levels somewhat above those of atmospheric air and primarily affects the lungs.

This paper endorses the standard and established methods for avoiding CNS oxygen toxicity, and suggests a slightly new twist on another established procedure for managing exposures of longer duration, such as a dive project requiring long exposures every day for several days.

Avoiding CNS toxicity

CNS oxygen toxicity can lead to a convulsion and is thus extremely dangerous to a diver. The approach recommended here for avoiding CNS toxicity is the one you learned in diving school: **Limit the exposure to high PO_2.** Safe exposure duration is a function of the PO_2. These levels are detailed in the USN and NOAA diving manuals, and are reprinted everywhere, including Table 1.

The table from which these values were taken is familiar to all trained divers, but as given here it seems to be missing some things. It is indeed missing two things, the "exceptional" limits and the limits for levels below 1.5 atm PO_2. The exceptional limits are not recommended for working scientific or sport divers, nor are they needed. However, oxygen breathing under controlled conditions at rest--such as during decompression--can be excepted. The limits below 1.5 atm are covered in another way in the next section.

Table 1. USN oxygen limits for avoiding CNS toxicity.

The limits for normal exposures to oxygen assume low or moderate exercise, no breathing restriction or CO_2 buildup, and no unusual oxygen exposure before this one. The "body" limits apply for exposure to levels less than 1.5 atm. (Adapted from USN and NOAA Diving Manuals and the Repex report.)

Maximum PO_2, atm	Exposure time, min
1.6	30
1.5	40
1.4	(use "body" limit)

The basis for this approach is that the **normal** limits in the manual are conservative but quite realistic for exposures to PO_2's of 1.5 atm or above, but are overly conservative and unrealistic at below 1.5 atm. Because of the potential seriousness of an inwater oxygen convulsion, it seems prudent to use the more conservative limits in the CNS range above 1.5 atm. Levels below 1.5 atm are extremely unlikely to result in CNS toxicity no matter what the duration of exposure. The part of the USN table covering exposures below 1.5 atm is not needed to prevent CNS toxicity, and is inappropriate for body or lung toxicity (see next section).

The American Academy of Underwater Sciences sets a limit of 1.5 atm (mentioned in the AAUS manual in the section on surface supplied diving, 1987), but does not mention the duration of exposure. For enriched air diving the operational penalty is small if 1.5 atm is never exceeded, since working times above that level are short anyway. For an extra measure of safety do not exceed 1.4 atm when working at maximum depth.

Another important thing is to be sure the PO_2 is what one thinks it is. Enriched air divers should know how to calibrate and use the oxygen analyzer, should make sure tanks are well mixed, and should check tanks again before use.

Avoiding chronic oxygen toxicity

The "other" type of oxygen toxicity is generally thought of as "pulmonary" or "lung" toxicity, and indeed that is the most prominent and most discussed effect of longer exposures to hyperoxia at above about 0.5 atm PO_2. This consists primarily of chest and airway soreness, coughing, and a reduction in vital capacity. A number of other minor symptoms such as headache, fatigue and loss of aerobic capacity, numb fingertips, paresthesias, and various aches and pains have also been noted, so to include these non-pulmonary symptoms we are calling this syndrome "somatic" or "whole-body" oxygen toxicity, rather than limit it to "pulmonary." This toxicity develops over time and comes on faster at higher oxygen levels. Recovery takes place when the exposure level drops below about 0.5 atm.

Looking at various exposures for one or two days, one to two weeks, and about one month has convinced some colleagues and me that an algorithm for controlling this phenomenon would work best if it considered the **average daily exposure** "dose" over time intervals in the order of days, and that the dose would have to be related to the number of days of exposure. We assume also that at the end of the exposure the diver will have a few days with no hyperoxia.

The method requires a bit of bookkeeping, but gives a clear and useable set of limits that have few uncertainties and are consistent with both experience and physiological principles. The procedures have been subjected to limited laboratory testing, and have been written up as part of new procedures for excursions from an undersea habitat using nitrox saturation (Hamilton, Kenyon, and Peterson, 1987; Hamilton, Kenyon, Peterson, Butler, and Beers, 1987). The procedures and the project use the name Repex. (The set of reports is available from NTIS (703)487-4650 as PB88-243894/AS, and they take telephone credit card orders.)

To keep track of the exposure, the oxygen dose, we used the classical UPTD or CPTD--unit or **cumulative pulmonary toxicity dose**--developed at the University of Pennsylvania (for a review see Harrabin et al, 1987); this work was done in the late '60's and early '70's. The unit pulmonary toxicity dose is roughly equal to an exposure to one atm PO_2 for one minute. This dose unit is well established, but it has not been shown how to use the CPTD to control exposure on a continuing, day-to-day basis. Specifically, there has been no method for dealing with **recovery.**

Our observations are that for a single day the dose can be rather high, say 850 or so units, but that if the exposure is for two days the **average** dose per day has to drop to about 700 units; if the exposure is for 3 days the daily dose can be 620 units, and so on until for an exposure of 10 to 30 days the average daily dose has to be about 300 units. We have put this into a chart and a graph, Figure 2.

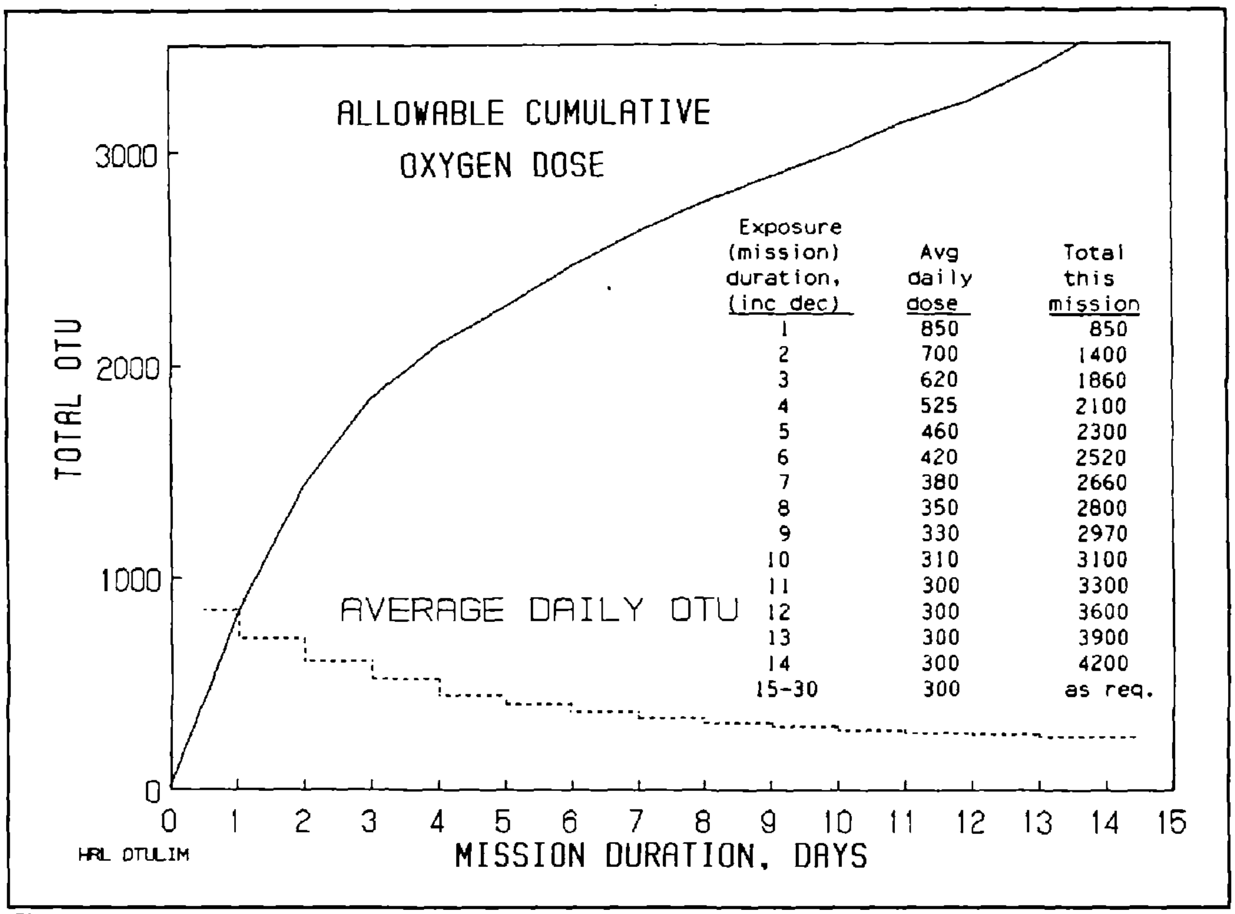

Figure 2. Repex method of controlling multiday oxygen exposure. Tolerance depends on the duration of the multi-day exposure. The daily dose is a function of mission or job duration, allowing higher daily exposure for shorter jobs.

The chart in Figure 2 shows a limiting oxygen dose as CPTD over one to several days. The solid curve is the cumulative tolerable dose, and the dotted line shows the daily average doses for different exposure durations. The total dose over the exposure period should not exceed the solid line.

This method takes care of the **recovery** problem. Our observations suggest that it does not matter much how the exposures are distributed around the day as long as the daily exposures are roughly similar and the accumulated total number of units does not go above the line. The formula and tables for calculating CPTD are given in the Underwater Handbook (Shilling et al, 1976).

Individual sensitivity to oxygen varies. These are estimated average levels for operational diving. We expect an occasional individual to feel some chest tightness or even soreness at the end of a maximum exposure, which will recover without therapy in a few hours or a day or two after exposure is reduced below 0.5 atm PO_2. The limits might have to be reduced for especially sensitive individuals.

Summary of oxygen control

To review these recommendations for control of toxicity due to excess oxygen exposure, CNS toxicity can be avoided by staying within the standard USN oxygen exposure limits (time and exposure level) for exposures above 1.5 atm, or better yet just stay below 1.5 atm PO_2. For exposures below the CNS limits determine the mission duration and keep the average daily dose or the total dose below the Repex levels for that exposure.

MIXING AND THE POSSIBILITIES FOR HELIUM

The objective of enriched air diving is to get a **higher oxygen fraction** in the breathing mix. Several methods are in use for making enriched air mixes. These may be done "on line" or the mixtures may be mixed and put into gas storage containers.

The on-line method used by commercial diving companies is to add oxygen to air with a "blender" at something near normal supply pressures and pipe it directly to the diver. Normally a supply of premixed gas is on the same manifold and can take over if the blender supply fails. The oxygen level should be monitored continuously, and since it is a primary risk factor should be on an alarm system. This method conceptually is quite safe, because the main gas is air and no matter what the deviation the oxygen level will not fall below that of air. The possible risks are that the oxygen level might get too high, or if it were to be too low and go unnoticed the decompression could be compromised.

Another method where the mix is made at the time it is used is with a closed rebreather unit. This is practiced by the U.S. Navy with their Mk15/16 units; these sets provide a constant PO_2 of 0.7 atm. Other rebreathers, including some "semi-closed" units, also fall in this category, and they may or may not maintain a constant PO_2.

Premixes are made by any of the normal mixing methods, including the use of the some of the blenders followed by recompression into high-pressure storage. The most common method for the scientific diver is mixing by partial pressures, usually directly into the scuba tank which will be used for the dive; this is followed by a check with an oxygen analyzer. Air and oxygen are normally used as the supply gases, but one could also start with oxygen and nitrogen.

Incidentally, once they are mixed gases will not separate, but if never completely mixed they can stay layered for days or weeks (this is more of a problem with heliox than enriched air).

Why nitrogen? Comparison with helium

At least two of the methods of making a high-oxygen mix of nitrogen and oxygen might just as well use helium. These are the rebreather and any mixing method that starts with pure nitrogen. This section discusses this option, because the advantages of helium make it worthwhile to consider using this gas instead of nitrogen as the inert gas.

Normally the basis for making enriched air is to add pure oxygen to air. This makes sense, because air is cheap and good quality air is readily available, and air already has a safe level of oxygen mixed with it. These two factors, plus of course the cost factor, are good reasons for choosing nitrogen as the inert gas.

If the method allows helium to be used as the inert gas with no increase in the effort required or the operational complexity, then it might be a better choice to use a heliox mixture rather than enriched air nitrox. This would certainly be the case if the mix is produced in a rebreather, and would likely be true in certain cases where the mixtures are made up and stored in high pressure tanks. The small extra cost of the helium gas is well worth it if there are no other labor or operational costs.

Helium is far easier than nitrogen to **eliminate** in decompressing without risk of DCS (decompression sickness). One possible problem with helium is that there are no NOAA-published **tables** for heliox diving. For the type of diving in question there are some USN tables that can be used, but a better approach would be to use tables developed for the specific application. Some heliox tables are longer than air/nitrox tables for the same dives.

Thermal effects and mis-impressions

One reason sometimes given for not using heliox for diving in the air range is that helium is believed to cause excessive heat loss through the respiratory tract. Helium does indeed have a higher heat conductivity than nitrogen. This makes a person **immersed in a helium atmosphere** lose heat several times faster than in air, and this effect increases with increased pressure. The same effect would prevail if a diver were to fill a dry suit with helium--some who have done this say it the suit might as well be filled with water.

But the heat removed through the respiratory tract is removed more as a function of heat **capacity** than heat **conductivity**. Exactly how the actions of these two physical principles are divided has not been determined, but a good case can be made that heat loss in a heliox dive in the air range would be less when breathing heliox than when breathing air (Schmidt, 1982); because air has a greater density, if equilibrated it will remove more heat. While there may be some thermal conductivity action that would cause heliox to become better equilibrated with body temperature than would air, this effect should not be great and there should still be a lower heat loss with heliox. Also, helium feels colder to breathe, and it cools the upper respiratory tract more than air. Definitive experiments to test this phenomenon have not been performed, but in a recent operation divers breathing heliox but with air in their suits have reported no thermal problems from breathing heliox (Stone, 1987). The best gases for suit insulation are argon and carbon dioxide; because of the physiological effects if it gets in the wrong place, argon would probably be the best choice, but that would depend on the circumstances. Counterdiffusion effects with argon would not be a problem, but CO_2 against the skin can cause irritation where there is moisture.

Density

The lower density of helium is a real but relatively small advantage in the air diving range. Not only does this reduce work of breathing, it tends to result in a lower carbon dioxide level and would therefore reduce the risk of oxygen toxicity.

CONCLUSIONS

Enriched air diving offers a worthwhile decompression advantage to diving operations in the range of about 60 to 120 fsw. Decompression tables for enriched air diving can be determined from existing tables for specific mixes, from standard air tables using the "equivalent air depth" with at least as much reliability as the standard table, or calculated on a custom basis for special situations. Oxygen poses a real hazard at the levels of CNS toxicity and can cause diverse but less serious symptoms from longer exposures at lower levels; both of these can be managed by limiting exposures appropriately. Helium should be considered as an alternative to nitrogen as the inert gas in situations where it makes economic sense.

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Discussion following Dr. Hamilton:

DR. HAMILTON: Surely you noticed that I read my talk from this computer.

DR. VANN: Is this a first?

CAPT HARVEY: Are your batteries fully charged, Bill?

DR. HAMILTON: The batteries are good for about two hours, and they are fully charged, so let's carry on.

Let me call your attention to the fact that "EAD" can mean two things, "equivalent air depth," which is what I think most people think of, but it also could stand for "enriched air diving." That is simply just to call attention to a possible source of confusion.

DR. CROSSON: You have given a lot of different topics; where do we go from here?

DR. HAMILTON: First, let us go to some people who can give us some practical experience in the use of the special gases; that follows later in the Workshop.

Where do we go from here? I wanted to suggest that there are perhaps new things that could be thought about in addition to a single "nitrox" mix. I wanted to show the advantages of a specific "custom" calculation as compared with taking things off of the tables. It is better, but I do not have a good example handy. The enriched air concept is good. It offers some very nice advantages over a small depth range. We are here to tell people about that.

DR. CROSSON: One current issue is repetitive diving. What are your feelings on equivalent air depth on repetitive diving?

DR. HAMILTON: Dr. Wells, does the NOAA Diving Manual deal with repetitive diving?

DR. WELLS: Yes.

DR. HAMILTON: You can do it. You just figure it on the basis of the partial pressure of nitrogen that you are actually using; use the repet group of the table that you end up with. It works to the same extent that the repetitive mechanism itself works, but you do not have exactly the same situation. You have a different pattern of gas loading after an enriched air dive because you will be there longer than you would be for an air dive. If we can assume that the repetitive mechanism works equally well across the board with air (for different dive durations and depths) then it should work fine with enriched air diving.

DR. WELLS: Bill, you mentioned the EAD principle or concept or whatever we want to call it. Do you believe the repetitive dive aspects, in that the tables published in the older NOAA Diving Manual are identical in format to the air tables and you can enter them?

DR. HAMILTON: You can use them and enter them just as you would the air tables. Does the NOAA Manual have a repet table or do you just use the U.S. Navy repetitive groups?

DR. WELLS: If you use the upper (more conservative) equivalent air depth and enter the tables, you come out with repet groups. The residual nitrogen time table is identical in format, but has different numbers in the column because they mean different things. One can use these exactly as they would air tables for single dives or repets.

DR. HAMILTON: Although they might not be exactly the same physiologically because you are going to have the gas in slightly different distributions, I think they certainly will work as well as they do with the air tables themselves.

There is a lot of "J factor" in the repet tables, isn't there, Claude?

CAPT HARVEY: You just stole my line. There is a lot of J factor in the repet tables. One other comment. One must separate an open circuit enriched air concept from a rebreathing concept because of the greater complexities involved with a rebreather.

DR. HAMILTON: A rebreather uses a constant PO_2; that is a different thing. I did not address that specifically, although you can see what you have in Figure 1. With a rebreather you can go all the way across the board and it works very well. It will work all the way over to where it intersects with the air depth, and from there it is better because you can do things that will not be safe to do with air.

CAPT HARVEY: I want to point out that the complexities of planning your dive are magnified when you go to rebreathing units. It simplifies some problems, but it also makes it more complex to plan, train, and work with the tables themselves. Also, there is a difference between a semi-closed system and a totally closed system, and they require different planning. I am not saying one is better or worse. You simply have to plan for them. A premix and an open circuit rig is the simplest of all.

MR. GALERNE: I am very concerned about sport divers using mixtures. My experience in the last forty years is that they never know what depths they are going to, and a mixture which is adequate at sixty feet can be deadly at a hundred feet. If somebody does not know exactly what he is doing and starts to play around on the bottom, he is likely to end up as a casualty. You have no feeling of danger, you feel you are perfectly all right.

We treat divers at our facility every weekend in the summertime; they seldom know where they have been, a hundred feet or where. If they use nitrox at fifty feet, it is perfect. But some mixtures at a deeper depth would be deadly.

DR. WELLS: What we are teaching is NOAA Nitrox I (32% oxygen, 68% nitrogen). This is the prescribed mix that has been published for ten years in the NOAA Diving Manual. It has been accepted by peer review and by workshops in the past. The teaching of NOAA Nitrox I to sports scuba divers is one thing, but the teaching of the equivalent air depth concept can be another thing. I do not profess teaching the EAD concept to recreational divers.

DR. HAMILTON: That is a good point. I am glad you made it because it partly answers Andre. It also hits Dudley, because he is interested in a highly technical scientific diving community of people who should not be quite as blase and naive as the ones Andre is concerned about; these divers have to plan their missions, and presumably they should be able to manage the depth versus the gas. But this is a slightly different situation. We are trying to talk about both of those things here.

Dick Rutkowski is teaching a set mix where you use this one mix and use a set of tables for this mix. You do not have any choices. You just do it, and you can stay out of trouble fairly well with that. But you still have to stay within some depth limits.

MR. RUTKOWSKI: In the south Florida area they are sinking some wrecks. Divers are going out on these wrecks; the majority of them are 100 feet or deeper. Of course, we do not use nitrox at 130 feet. Two wrecks near Key Largo are right at 122 feet and you have to go a half mile away to get away from the 122 foot depth. We know that divers are going out there and pushing the 10-minute no-stop decompression limit. If I can teach people how to do 20 minutes and do it more safely, then I think I have an obligation to do that.

DR. DAUGHERTY: What is the J factor you and Claude referred to? Is that a fudge factor?

DR. HAMILTON: Not exactly. As with any other printed tables, each section in the repet procedures chart is a group. That is to say, it covers a range. When you enter the repet table, the table you started with covers a range. For example, when you are at 64 fsw, you use a 70 fsw table. Then your repet table covers a range; you enter the chart and determine a surface interval, and that covers a range. Then you go back and get another table from that, and that one also covers a range. Because the choices do not hit at the very edge of the range, this process involves a certain amount of conservatism. That conservatism is due just to the mechanics of the way it is presented.

But with the tables themselves, they used a single compartment (a half time of 120 minutes, I think) to compute the first dives, and then for the repet dives they looked at the gas loadings that were present at the time of the next dive in that particular compartment, and based the repetitive mechanism on that direct calculation for a variety of situations. One compartment had to be used, otherwise they would have had a hodge-podge of complex relations.

Using a single compartment to monitor the gas loading at the start of the second dive means you are closing your eyes to a lot of other compartments. So when this was done, they put in buffers to deal with the other compartments that might also be excessive in the second dive.

Ron Nishi took a slightly different approach when he did the 1983 DCIEM repetitive tables.

CAPT HARVEY: So the "J factor" is the difference between what you would get if you were to figure the exact depth and the exact time and work your way through the process, as compared with the depth and time that you end up with when you use the charts.

DR. HAMILTON: To summarize, there are two things. One is because everything is in ranges, and you have to use the upper limit of the range for anything that falls within the range.

The other thing is that when the repet tables themselves were done some extra conservatism was put in to cover the fact that a single procedure has to deal with a wide variety of exposures. So there was actually conservatism put into it.

If you were to use the repet tables all at absolute face value you still would have a fairly conservative repetitive dive based on an algorithm that itself was not too conservative. My impression is that they work. However a lot of commercial companies just flat will not use repetitive diving. Maybe Andre can explain why.

MR. GALERNE: In listening to you for the last hour I was pretty sure you had read my paper because it is exactly the same. In fact, maybe now I do not have to give mine.

One point I would like to mention is the use of nitrox for diving at altitude. Since you did not mention it, that is the only reason I believe you have not read my paper. Maybe you can talk about that. That is an important application of nitrox, diving at altitude.

DR. HAMILTON: That is a good point. I really did not think about it, which proves I did not copy your paper. It certainly makes sense. At altitude there are even more benefits of enriched mixes. And there is less of a high oxygen problem.

DR. CROSSON: Say, for example, you have a project that is going to last about five days, and you want maximum bottom time but for logistical reasons you can not take all of the oxygen you want. Would you use the enriched mix for the last dive of the day? Would you use it on the last couple dives of the operation?

DR. HAMILTON: If you have a full mission plan you may find certain situations where a longer dive will make the plan better. That would be one thing. In other words, see how it fits into the operation.

As to whether you would be better off using the enriched air as the last dive of the day, I think an enriched air dive is more conservative than a basic air dive. I gave the logic for it. I would use it at the end of the day.

But again, for example, you might be able to get a job finished if you can stay two hours using enriched air whereas with air it might take two or three shorter dives for the same working time; in this case saving your enriched air until the end of the day would not be efficient. So I would let the operational plan decide. If you can finish the job with a single dive the exposure is far less and the operation is safer. That is something that I think needs to go back to the diving control boards if the people are having trouble selling enriched air. If you can do in one dive what you would otherwise require two dives to do, your overall operation is easier, less complex and, therefore, probably a lot safer. Physiologically, however, I agree with what you are suggesting by your question, that the enriched air dive should be last because it gives a more conservative decompression.

MR. GALERNE: Let me make two points and I will not have to read my paper. I am concerned when I hear some of those comments, because you cannot use equipment back and forth. Most compressors are oil lubricated. If you use mixtures of oxygen over 27%, you are in the flash zone. So forget this. You need to be very, very careful. If you fill a tank previously used for air with a 50-50 mixture, for example, you take a chance of explosion.

So I suggest you forget this idea of going down with scuba diving equipment one afternoon then switching to mix the next day, because [to do this safely] you have to clean your equipment between the two procedures. If not, you will have an accident. Any gas that has more than 27% oxygen is in a flash zone. You can have an explosion.

> [EDITOR'S NOTE: The hazard expressed by Mr. Galerne is indeed correct, but the use of 27% as a divider between safe and dangerous is a somewhat arbitrary choice. In practice values ranging from 27 to 40% are used to determine when oxygen-safe practices have to be followed. **The fire risk due to oxygen-enriched gas mixtures increases continuously as the oxygen content increases.** Compressed air itself can be a fire hazard. This Workshop did not address the matter of handling enriched oxygen mixtures, and those interested in using oxygen-enriched mixtures are strongly advised to seek expert advice.]

Apart from the physical situation of switching gases, what about the physiology? How do you switch from table to table if you dive first with an air table and then with nitrox?

DR. HAMILTON: Morgan just pointed out that if you are using something like the NOAA Nitrox I tables that you can use the same repetitive groups, that they are transferable between the USN air tables and the NOAA Nitrox I tables.

The best thing might be to calculate or compute the dive for that specific situation, as will be done in the next version of your dive computer or I can do with this one.

CAPT HARVEY: Let me make two comments that bear on the question of when do you use enriched air as compared to regular air. The Hawaiian divers, many of whom set fishing nets, do repetitive dives throughout the day. They will do two to as many as four or five dives; they do their deep dives during the morning and then their shallow dives later. It would seem sensible that you use air first, with the higher nitrogen pressures, then use enriched air later in the day. This is a good example to follow.

DR. HAMILTON: They are actually decompressing. If they skip the last dive of the day, they may get hit.

CAPT HARVEY: The second comment is that it has been observed in tunnel workers that when they are unacclimated--that is, at the beginning of a week when they have not been diving that much--that they seem to be more prone to decompression symptoms. If your divers are unacclimated, I can make a case for using the enriched air for the first day of a mission while they get used to their diving.

MR. PARKER: How do you feel about the situation in which scientists diving in shallower depths (at less than 40 feet) where you mentioned there really was not much of an advantage of using enriched air, but doing this over an extended period of time. They might go out for a seven or eight day mission and dive for six hours a day, and towards the end of that might show slight behavioral signs of decompression sickness?

DR. HAMILTON: The point here is that even though you may have plenty of bottom time at the depth you are working, if you use enriched air it gives you a better decompression. That is to say, you are picking up less nitrogen. You are suggesting the use of enriched air not necessarily to extend the bottom time but to make the exposure less likely to cause decompression sickness. That is absolutely valid.

This goes back to Dud's question and Claude's comment. There seems to be trouble in the beginning for people that have not been diving, and trouble after several days of diving. We do not know the physiology of either of these phenomena as well as we would like.

MR. GALERNE: The decompression accident is mostly because the guy wants to go home quickly.

DR. HAMILTON: Or he goes on overtime if he is in the chamber. There are other factors involved, but you still see these two phenomena. We see more DCS in the unacclimated diver; there is plenty of evidence that people that have not been diving are not as tolerant as people that have been.

Then there is the business of the multi-day diver, where the dives seem to be totally innocuous and he or she stops well within the repet limits, and everything on a day to day basis is okay, but the diver may end up with the bends at the end of the week.

MR. RUTKOWSKI: At our facility where we use guides to take divers out diving. At the end of the week as a precaution we have the guides breathe enriched mixes but have them use the air tables all day.

DR. VANN: Let me ask if anyone has experience or could describe this paradox between the effect of acclimation to DCS and the problem of multi-day diving? In your experience have you seen anything that supports either one of those phenomena, using either air or nitrox, or with any diving?

MR. GALERNE: We had a job for 18 months where we had people at 200 fsw seventy-five minutes a day every day, only leaving out Sunday, and we saw no problem. We saw no evidence of a problem with an accumulation of nitrogen, but we did have a presumably unrelated problem in the middle of the job. It may depend on the dives. Some are fragile. We do not have any proof of improvement, and we have not seen increased problems with multi-day diving.

MR. STANTON: I gather from your comments about heliox that if I have a project working at 170-180 feet there is no real advantage when these people go to the shallower sites at say 70 feet to switch over to nitrox, but rather we should just mix another heliox mix that would be appropriate for that?

DR. HAMILTON: If your situation allows you to mix heliox with no additional problems, so that the additional cost is only for the gas, it might be best. But you have to carry the heliox and the tanks it is stored in, and that is not a trivial problem. However, you still have to have a way of decompressing. I am not all that familiar myself with the use of U.S. Navy helium scuba tables, although they seem to be okay.

CAPT HARVEY: Dick brought up a good point. There is a lot of myth in diving, and it may not be easy to prove statistically what we have impressions of. Some of that has been embedded in our thoughts as almost folklore, but when we try to prove it statistically the data base simply is not good enough.

For instance, I said two things that really fall into the category of the magic myths of diving. One of them was about the Hawaiian divers, and the second one is the acclimation of tunnel workers.

Dick raises a question of scientific validity versus impression; there is an awful lot of impression here and unfortunately that is all we have to go on in making decisions on these things. I think as scientists we must identify when we think we are working with myth and when we think we are working with fact.

DR. HAMILTON: Does anybody know of a study where people have actually done a comparison of the results of enriched air diving versus air diving in the same partial pressures?

DR. VANN: More or less. The most significant study that has been done, although they did not call it that, deals with the EAD theory. I will present that.

CAPT HARVEY: Thalmann did some 800 dives at NEDU in which they looked at 0.7 atm PO_2; it was published in 1986. It compared 0.7 atm dives with air dives, and switched back and forth with the gases a bit; it did address some of what you were saying. [NEDU Report 8-85, 1986. Ed.]

DR. VANN: You have two different questions. (1) Does oxygen act as an inert gas? (2) How effective is oxygen in reducing your decompressional requirements? They are very related but they need to be addressed sort of in different ways.

CAPT HARVEY: I was going to talk on this tomorrow, but I think it is good to discuss it now. The Navy was developing algorithms for the underwater decompression computer that was to be used with our Mark 15 and 16 units. The work was done by Ed Thalmann primarily. He started out using air equivalent calculations. He gradually went into considering the oxygen delivered from the arteries. The current model does not treat oxygen strictly as a noncontributing gas. It takes a look at oxygen in addition to nitrogen. The point is he did not use strictly an equivalent nitrogen limit. He looked at the total gas.

DR. VANN: Does that mean he had to decompress from his oxygen?

CAPT HARVEY: Not totally. The model looks at the drop in oxygen from the arterial to the venous side and makes the computations partly based on the oxygen that gets through. I think that is as well as I can summarize it.

MR. RICCIO: Bill, I know you have done some studies on closed circuit breathing with elevated oxygen atmospheres. I was wondering how you might relate that method of enriching the air. Did you say you used 1.4 atm?

DR. HAMILTON: He is referring to a special case of this problem. Take 1.4 atm PO_2 as a maximum limit; you can breathe it all day long, and extend the dive range way out. You are not going to be happy breathing air at 300 feet, because if you were not narcotized and did not have a decompression problem, you would still have oxygen toxicity. So to get a mix you can breathe all day long, a nice way to do it is to buy a closed circuit rebreather from Mr. Riccio and set it for 1.4 atm of oxygen. The present U.S. Navy MK15/16 rigs do not have a dial that allows you to set the O_2 at that point, but it is possible to do it by setting it in a chamber.

If you set a rebreather at a constant 1.4 atm PO_2 then you do not have to worry about the depth as you would with air or another fixed mix (at least as far as oxygen toxicity is concerned). You cannot ignore depth, of course, because the inert gas is still a function of depth and your table has to be depth related. We have done a set of tables for heliox with a rebreather and a constant 1.4 atm PO_2 and found phenomenally good results in decompression in the range of 250 to over 400 fsw.

We used Thalmann's model, the exponential-linear or "E-L" (Thalmann, 1984). It is another kind of "special-mix" diving. It is actually not enriched air because the oxygen can have lower fraction of O_2 than air when you are at the depths mentioned. It is really not relevant to the Workshop, but it is worth mentioning as a new capability that just came out in the last year or two.

NITROX DIVING WITHIN NOAA: HISTORY, APPLICATIONS, AND FUTURE

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Dr. Wells is the NOAA Diving Officer and the originator of the "NOAA I" mix and method for nitrox diving published in the NOAA Diving Manual; this is currently the leading source of information on nitrox diving.

ABSTRACT

Wells, JM. 1989. Nitrox diving within NOAA: History, applications, and future. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

NOAA has had for several years a program for using enriched air nitrox mixtures for scientific diving. The NOAA approach is to use a mixture designated NOAA Nitrox I, which consists of 32% oxygen, balance nitrogen. This mix, NNI, is useful over the range 50 to 130 fsw, and offers time-saving advantages in both no-stop dives and repetitive dives using no-stop techniques. NOAA has devised a mixing system for preparing NNI, which works by adding oxygen to a compressor intake and monitoring the output. A method of labelling scuba tanks using a 4 inch green band on a yellow tank has been adopted. NOAA Nitrox II will be 37.5% oxygen.

INTRODUCTION

Air has been used as a breathing gas by divers since the beginning of diving. Its principal advantage is that it is readily available and inexpensive to compress into cylinders or use directly from compressors with surface-supplied equipment. It is not the "ideal" breathing mixture because of the decompression liability which it imposes. Since decompression obligation is dependent on inspired nitrogen partial pressure and time, not "depth and time", this obligation can be reduced by reducing the nitrogen content of divers breathing gas and substituting for the removed nitrogen a gas which is metabolized away by the body, i.e., oxygen.

The toxic properties of oxygen at elevated pressure limit the depth and time to which it can be breathed pure or as a component of a nitrogen-oxygen (nitrox) mixture. If both the toxic properties of oxygen and its decompression obligation reducing properties are taken into account, an "ideal" gas mixture for any depth/time combination can be produced. Such a mixture would offer the maximum decompression advantage without the risk of oxygen toxicity. Advantages of such a mixture relative to air are: 1) extension of "no-decompression" time limits, 2) reduction of decompression time if no-decompression limits are exceeded, and 3) reduction of residual nitrogen in the body following a dive. The latter would either increase the time allowable on repetitive dives or reduce the surface interval required to make repetitive dives, or both.

The decompression procedure which must be followed when nitrox is used is based on the concept of "equivalent air depth" (EAD). This procedure equates the inspired nitrogen pressure of a nitrox mixture at one depth to that of air at another depth, the EAD. This procedure has been used for over 20 years with semi-closed and closed-circuit mixed-gas underwater breathing apparatus. Such equipment is both very expensive and complicated.

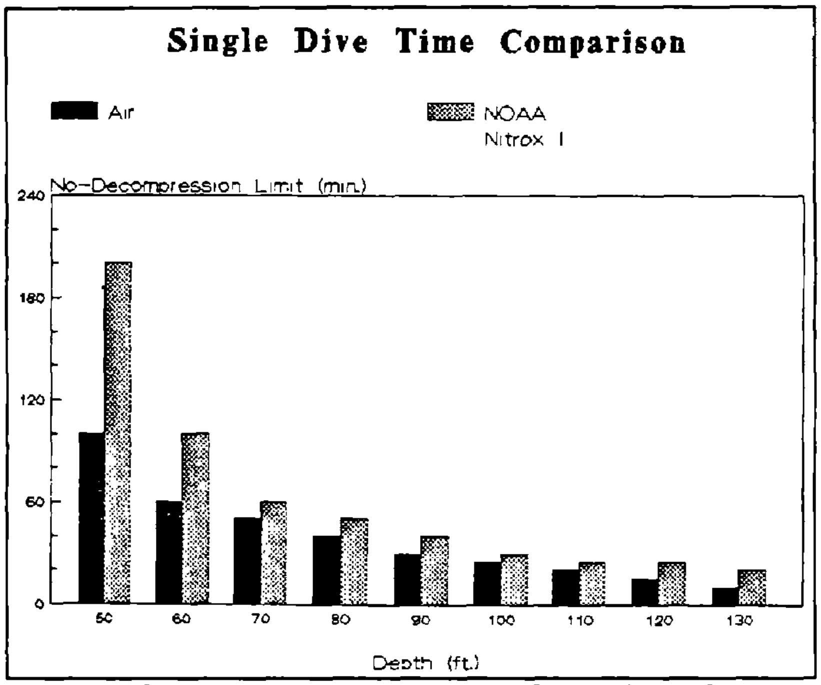

Figure 1. Single dive time comparison. Comparison of no-stop ("no-decompression") limits of air and NOAA Nitrox I.

NOAA NITROX I

In 1978, NOAA introduced diving procedures and decompression tables for a standard mixture of 68% nitrogen, 32% oxygen called NOAA Nitrox I (NNI). It can be used with normal SCUBA or surface- supplied equipment, and is the best general-purpose nitrox mixture for use in the 30- to 130-foot depth range. The NNI tables (Appendix E of the NOAA Diving Manual) are identical in format and use to the U.S. Navy Standard Air Decompression Tables, thereby eliminating the necessity of learning to use a new set of tables and providing a means of mixing air and NNI dives. During the last few years, there has been an increase in the acceptance and use--and misuse--of nitrox by the diving

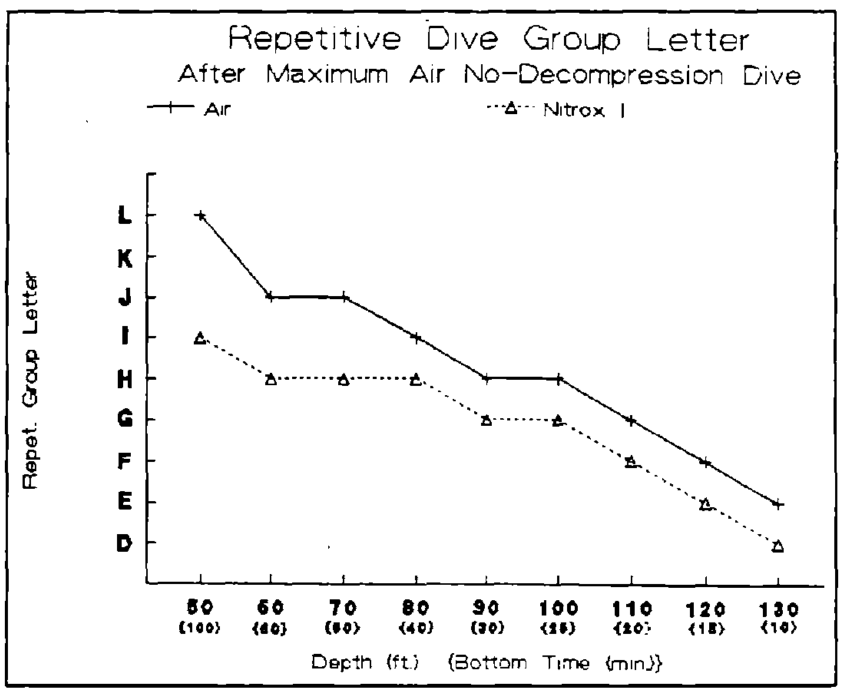

Figure 2. Repetitive group dive letters. Comparison of repetitive groups of air and NOAA Nitrox I.

misuse--of nitrox by the diving community. Figure 1 compares the no-decompression limits of air and NNI.

The use of NNI approximately doubles the no-decompression limits at most depths. One "not-so-obvious" advantage is the extension of useful "on-the-bottom" time. At 130 feet, the no-decompression time for air is 10 min. while the NNI no-decompression time is 20 min. If two minutes are required for descent, air gives the diver 8 minutes of useful time at depth while NNI will allow 18 minutes. Figure 2 shows the repetitive groups for air and NNI for dives to the same depth and time. The repetitive groups and thus the residual nitrogen times are significantly lower for NNI. This is of great value in reducing the surface interval between dives and/or extending the time of repetitive dives. The net result of all of the above is <u>more bottom time per day.</u>

Figures 3 and 4 show the advantages of nitrox use in repetitive diving to several depths and with different surface intervals.

Economics and time savings are key factors with respect to diving operations. Breathing gas mixtures are normally prepared by mixing oil free, pure gases in appropriate proportions and checking the mixtures with oxygen analyzers. The expenses associated with the purchase of gas, equipment, and utilization of qualified personnel can be significant. So

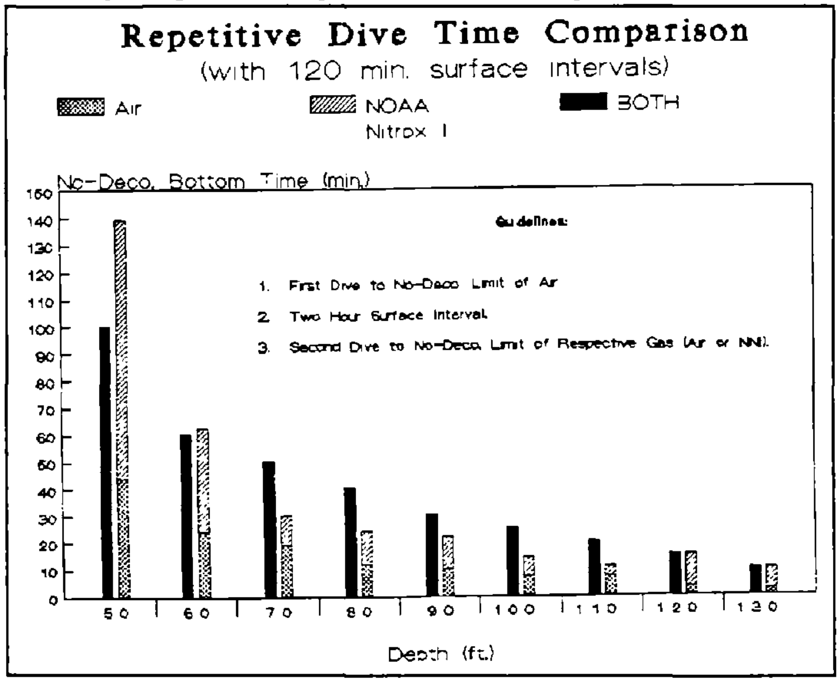

Figure 3. Repetitive dive time comparison, 120 m interval. Each pair of bars shows first (dark bar) a dive to the air no-stop limits at that depth. The second bar shows time allowed on second dive with air (cross hatch) and Nitrox I (diagonals).

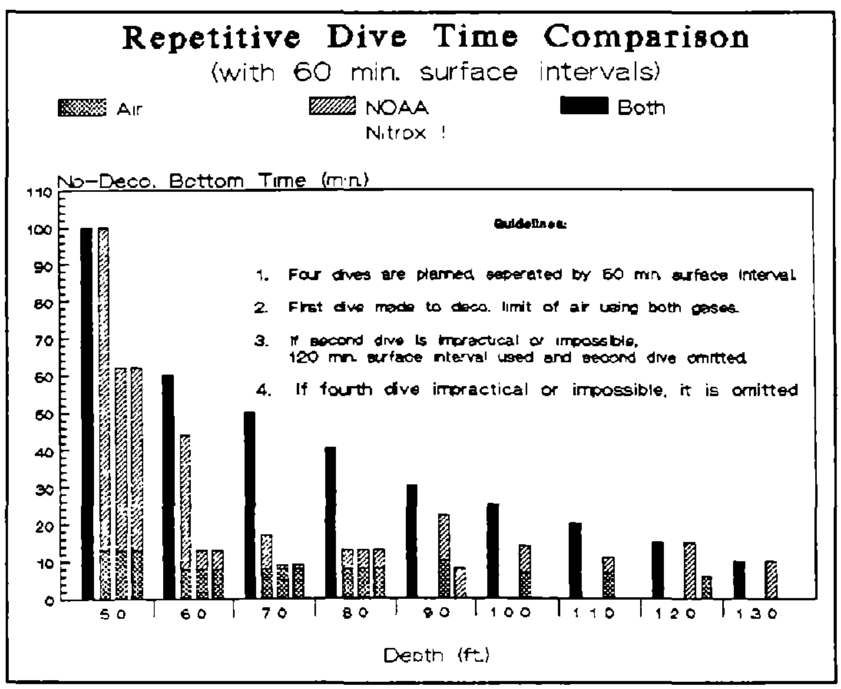

Figure 4. Comparison of repetitive dive time. First dive is to full no-stop Air limit, with both gases. Cross hatched bars show allowed time with air, diagonals show time with Nitrox I.

can the consequences of shortcuts and/or poor procedures. For example, traces of oil in a high pressure oxygen mixing or pumping system can lead to an explosion. Too much or too little oxygen in the mixture could lead to oxygen toxicity or decompression sickness. The extreme case of accidental use of pure gases (N_2 or O_2) has proven to be fatal.

Personnel time and ship time associated with diving operations can also be significant. The increase in useful "bottom time" which is provided by the use of nitrox mixtures often makes it very cost-effective. The reduced nitrogen pressure at depth slightly reduces nitrogen narcosis. During ascent and decompression stops, it also reduces the probability of decompression sickness.

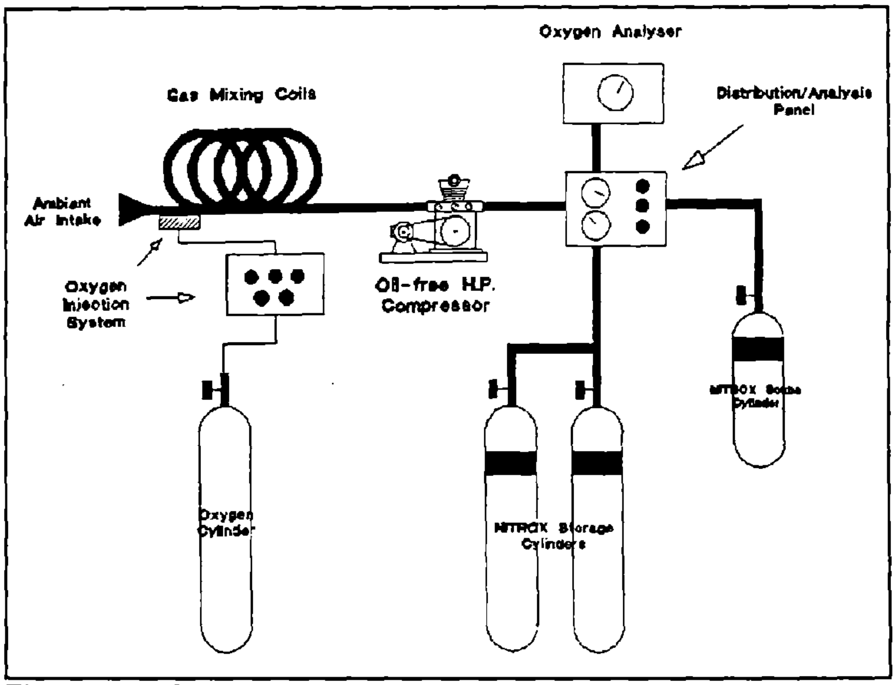

Figure 5. NOAA continuous mixing system.

The subjective post-dive feeling of "well-being" (reduced fatigue) reported by some users suggests that sub-clinical DCS is reduced. Subtle effects of increased oxygen pressure on nitrogen uptake and elimination remain to be determined.

NOAA GAS MIXING SYSTEM

The NOAA Diving Program recently developed a system for mixing air and oxygen at atmospheric pressure, and compressing it to pressures of over 3,000 psig. Oxygen concentrations from 21-40% can be easily and accurately mixed. The system utilizes a "non- oil-lubricated" compressor, and the design is such that both large storage cylinders and SCUBA cylinders can be filled and/or cascaded simultaneously. This feature eliminates the requirement for a gas booster pump, and significantly reduces the cost and time required to prepare nitrox.

Three NOAA Continuous Nitrox Mixer units (Figure 5) are currently in use at NOAA diving units, and Hyperbarics International recently installed a system on Key Largo. For the preparation of large quantities of nitrox (in oxygen-clean systems), mixing of pure oxygen and oil-free air is probably the most "time-effective" method. The use of pure oxygen and nitrogen is an obsolete method of preparation.

NOAA has established a color coding and labeling system for nitrox mixtures (Fig. 6), and uses dedicated cylinders for nitrox. Air is never put in nitrox cylinders and nitrox is never used in air cylinders. A final analysis for oxygen is conducted by the diver prior to using NNI.

Another nitrox mixture, NOAA Nitrox II (NNII) is currently being evaluated. It contains more oxygen than NNI, thereby reducing the decompression obligation even more, but its use will be limited to depths of 100 feet or less.

TRAINING

Training of NOAA working-level divers in the use of nitrox in open circuit SCUBA requires one day; a four-hour lecture period and a four-hour practical session. The lecture portion includes a heavy emphasis on oxygen toxicity. The potential consequences of misuse of nitrox, decompression and repetitive diving procedures, and mixing air and nitrox repetitive dives are covered. The practical sessions include safe handling of oxygen-rich gas mixtures, gas sampling, and oxygen analysis. Brief written and practical exams are given in the afternoon. These divers are "users" of nitrox. Training in the preparation of mixed gases is considerably more extensive, and generally limited to unit diving supervisors or those divers responsible for diving lockers and breathing gas preparation.

Due to the extra cost, equipment, complexity, and training required for the use of nitrox, its use in NOAA is currently limited to those diving units to which it can make a significant contribution to cost effectiveness. As its advantages become better known, we anticipate more requests to establish mixing systems at diving units.

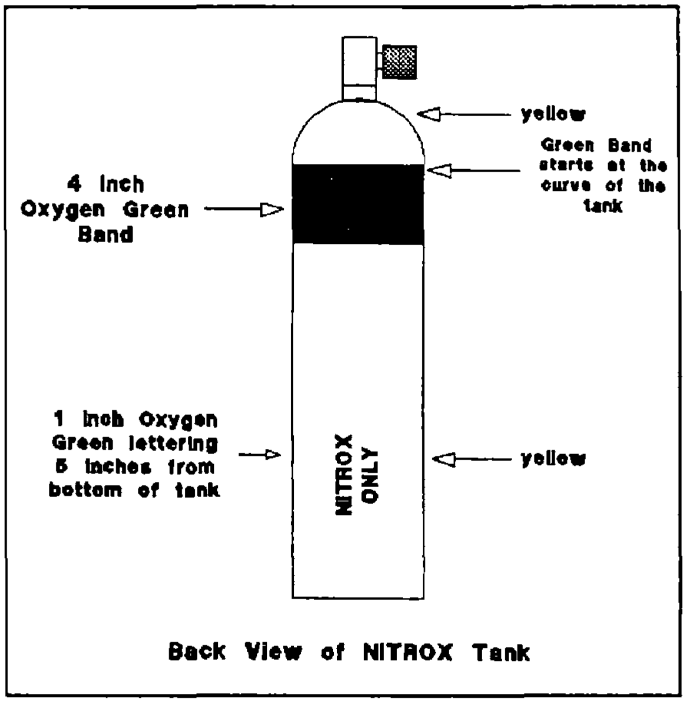

Figure 6. Markings for NOAA Nitrox I scuba tanks.

Additional comment by Dr. Wells:

DR. WELLS: Nitrox goes back quite a long way. In fact, my own initial interest in it was back in the mid sixties during Mark 6 training with the Navy where some of the richer mixtures there significantly increased the no decompression time and reduced decompression obligation and so forth. In those days this was a little more complicated than the scientific community was willing to accept, and economics entered into it there also because nitrox mixtures were prepared from pure oxygen and nitrogen. This was not only expensive but it was time consuming and required a fair amount of equipment. So nothing really happened in the scientific diving community for quite a while.

In the late seventies, I think 1977, when I was writing up the justification and the data base for what we now know as NOAA Nitrox I, I researched it a little bit more and found one reference to Chris Lambertsen back in, I think it was, 1943. He was quoted as suggesting that mixtures of nitrogen and oxygen be used to reduce decompression.

DR. LAMBERTSEN: I think it was 1943.

Discussion following Dr. Wells:

MR. RUTKOWSKI: We have been talking about one standard mix and the EAD concept. Would you give your philosophy on what NOAA intends to do to eliminate the problem of the EAD concept for operational purposes?

DR. WELLS: Good. Thanks for reminding me. You know, the 32% mix was designed using the maximum depth for normal scuba operations (130 fsw) and 1.6 atmospheres of oxygen. It is the best general purpose mix for scuba diving. As Bill has pointed out, the real range of this stuff is between 40 and I would say 130 fsw (you say 100), or so. That is the full range.

We know using the EAD you could calculate a perfect mixture, or the best mixture for any depth-time combination using both decompression and oxygen, staying within the decompression limits and oxygen toxicity limits.

We have another one on the burner now, that I have talked to some of the people in this room about. The reason NOAA Nitrox I is called that is because ten years ago I always intended to have a NOAA Nitrox II. We have not had the need for it, but now we do. The one we are looking at is 37.5% oxygen. The reason for that is that at 100 fsw this gives you a PO_2 of 1.5 atm.

Now, when we consider different mixes and go through the decompression limitations, we find out that decompression is no longer the limiting factor on the duration. Even in the no-stop dives, it is oxygen toxicity if we go by the Navy limits.

So Dick Vann gave me a bunch of his best guesses, and Peter Edel gave me a few of his on this 37.5% mix. In most cases the limiting factor in the single exposure is CNS oxygen toxicity and not decompression. So the limitation of a no-decompression (no-stop) dive is not decompression at all, it is CNS oxygen toxicity.

Now, there are other depth-time combinations where you can do better, in individual cases, but I am looking more at making these things sailor proof. We are going to have for the nitrox II another set of tables identical to the Nitrox I ones, and these will also look like the air tables.

So I do not want to give them a chance to really hurt themselves bad through simple errors. Oxygen toxicity is going to get you if you mess around too far out there, and most divers do not even know it exists. All divers know that you cannot dive deep on air because of nitrogen narcosis. That is probably why there are a bunch of bodies down in some of these caves. They had oxygen hits down there at 250 feet on air.

My philosophy on this is that these two mixtures, 32% and 37.5% O_2 adequately cover the nitrox diving range. I am making it as simple as I can, and I do believe those two mixtures cover the nitrox range pretty well. So for general purpose use, at least in our consideration where you turn these guys loose, that is what we are going to do.

MR. DINSMORE: On the question of EAD (equivalent air depth); what are your feelings on the validity of it with different mixtures?

DR. WELLS: I darn well better believe in it, shouldn't I? Obviously I think and the rest of us in NOAA think it is valid enough to use. The reason we are not using what I would call broad spectrum EAD is more for operational and behavioral reasons rather than physiological ones.

CAPT HARVEY: With the Mark 6 the Navy had a number of us using equivalent air depths for our decompression, and it certainly did not seem to be any less safe than the tables themselves were. I am unaware of any statistical incidence of the bends using the EAD for that range of diving.

DR. LAMBERTSEN: What I think we are saying is that from a physiological standpoint there does not seem to be any real reason why one cannot use any of these particular approaches to the fullest, whether it is oxygen or equivalent air depth or standard mixtures or regular decompression. That is going to be an easy one if we will just open our minds and realize we are using that information and not get hung up on it.

What you really have is a group of different organizations, each of which has a proper and normal function in the world. You have a commercial diving company. You have NOAA. The Navy has a different function from NOAA. Harbor Branch has a different function from any of these. Yet each one has to be able to control the manner in which it handles its diving operation so that it plays its role properly, takes care of its people and its functions, and see to it that the organization does not destroy itself by either carelessness or poor regulation.

I think we should avoid having anyone try to put it all into one pot so that one agency has to do everything, when it does not make sense at this moment for any agency or organization to do everything. We should try to let that agency have the information that fits its purposes. That does not mean the other purposes are no good. Some of us should be able to feel free to do exactly what is most sensible for that particular operation. Others could say, "We know we can do that, but we are not going to do it".

So I think what Morgan has described is national agency activities, the philosophy of a national agency which does not have to be seal team and it does not have to make a living in the offshore industry.

DR. WELLS: Agreed. I hope I was not giving the impression that NOAA is going to try to regulate this. We have enough trouble trying to regulate our own people. We do not need anybody else.

MR. GALERNE: For example, in the diving industry we practically never make a repet dive. We go to the bottom for the longest we can and spend the maximum time, but we practically never go up and down like a yo-yo. So we do not have too much experience in multiple dives.

In contrast I think it is unwise for the whole diving community not to have a specific set of diving tables for nitrox, because you do not get maximum capabilities by limiting yourself to one or two mixes. You can have a rainbow of mixtures and if you know how to use the mixtures you can have much better production. You can stay practically at 60 feet for three or four hours without decompression. But if you use a single mixture, you lose that.

So I think it will be important to see NOAA looking to have a set of decompression tables as a function of the mixture that can be used. Because, if you just play with a little variation in oxygen (which is a very novel possibility) I am sure you can find some people that can do that very quickly and very efficiently.

DR. WELLS: Yes, Dave Dinsmore, I think, has a little book in which he has tables for every percent of oxygen.

MR. DINSMORE: Every percent.

MR. GALERNE: As long as you can mix with that precision.

DR. WELLS: Our feeling right now, and we could change, is that it is not physiological. We realize full well that we are not maximizing the use of oxygen. It is also my feeling that the possibility of a traditional screw-up if we were to use this broad spectrum approach, or of having a few hundred divers running around out there all mixing their gases and trying to get the perfect gas, would outweigh the advantages of tailored mixes.

DR. CROSSON: Maybe you might expand a little bit more on the history; it is almost like NOAA paralleled what was going on elsewhere regarding the use of nitrox. Is it because of economics, because it is cheaper now, or did you have a specific need to get back into it?

DR. WELLS: I think economics is the driving force now simply because previously we had very little equipment. The equipment was expensive and the need was not there. It started snowballing on us now. The more we use it, the better we like it, the move advantages we see, and now everybody wants it. We can not keep up with a demand to put in gas mixing units, even though they are eight thousand bucks a piece.

DR. CROSSON: Does NOAA do oxygen tolerance tests?

DR. WELLS: Negative.

MR. RUTKOWSKI: An area to consider is the use of nitrox mixes for therapy purposes, decompression therapy purposes.

We have talked a lot here about the EAD concept. In decompression therapy, there are operational advantages of using the EAD concept for physicians or attendants. For example, for locking a physician into a chamber at 165 fsw pressure, we at NOAA over the last 15 years have used a 60/40 N_2-O_2 mixture. The reason for the 60/40 mixture is to make it sailor proof, but also we felt we could give that physician at 165 fsw 20 minutes of no-stop time.

Another advantage is narcosis. He can work with his patient with a much clearer head. So we use the EAD anywhere from 165 to 200 fsw with 60/40 N_2-O_2 mix call to give him as much operational advantage as we possibly can. Of course, we all know the oxygen level for the patient is somewhere close to what we would give using pure O_2 at 60 feet. Yes, we have been using the EAD concept for many years.

MR. GALERNE: You mean you feed the chamber with that?

MR. RUTKOWSKI: No, by bibs (built in breathing system).

And the other thing is there must be an attendant inside who is not on the high PO_2 in case the physician has a seizure. We require that safety practice.

DR. HAMILTON: That is a high level; at 165 fsw 40% oxygen gives 2.4 atm. I suppose you do not expose them to it for very long?

MR. RUTKOWSKI: No, definitely not.

DR. HAMILTON: Is that within the normal Navy limits?

MR. RUTKOWSKI: No; 1.4 atm used to be the allowable exposure, unstressed and at rest.

Remember, we have this physician in a chamber in a dry environment. We are looking for operational advantage. We have a safety person in there to watch him.

DR. HAMILTON: I am just asking how that compares with the published limits? You are saying that 2.4 atm is above the limits, right?

MR. RUTKOWSKI: Exactly, but we are definitely willing to press that limit for the operational advantages it gives us.

DR. HAMILTON: That sounds good.

DR. WELLS: It depends on which limit you are looking at. This is an acceptable limit for decompression or therapy, but not for a working diver.

Dick reminded me of another thing. We use the EAD in our chamber when training for saturation dives. Now we are talking about of mixtures of say 10% O_2, where the equivalent air depth is deeper than the actual depth. With the enrichments the EAD is always less (shallower) than the actual. This is where we get the advantage. We have had a fair amount of experience and have exposed a lot of individuals to gas mixes. In saturation the mix is the chamber atmosphere. We just blow pure nitrogen into the air-filled chamber equipped with a scrubber, and that fixes it; we have had no trouble with that.

DR. VANN: Morgan, when you were setting up your mixing system did you ever look at the alternative of using one of these differential membrane oxygen mixers from medical supply companies that are made to provide oxygen-enriched air for patients? Have you explored that at all?

DR. WELLS: Enough to know that you can use these things, and especially that you can stage them as well; but they are bloody expensive.

DR. VANN: That is a significant disadvantage.

MR. GALERNE: You are talking about the dome regulator?

DR. VANN: No, it is a semi-permeable membrane which has a differential permeability for nitrogen and oxygen, so if you put air on one side, you get a mixture rich in oxygen on the other side.

MR. GALERNE: By osmosis?

DR. VANN: By diffusion. The membrane resists the diffusion of nitrogen more than oxygen.

There are a number of standard systems on the market; you would have to do a long term analysis to see where your break even point would come, but they seem fairly straightforward and adaptable to this application.

DR. WELLS: I believe that we explored them up until we found the price tag.

DR. VANN: They are expensive, but are you not talking about $8,000 for your system?

MR. GALERNE: That includes the compressor?

MR. RUTKOWSKI: No, that only includes the oxygen membrane; then you have to spend another $45,000 more.

DR. CROSSON: We were looking at that at one time. We figured it would come to about $45,000 to come up with a workable system there.

MR. GALERNE: You can buy a mixing device (a gas blender). It is around $20,000 or above. You also have to have a compressor, but that is all. So you reach $30,000 in all of that.

DR. WELLS: Pure oxygen is pretty cheap. It is fifteen bucks for 200 cubic feet, so there is less than a dollars worth of oxygen in each scuba bottle.

DR. HAMILTON: Where the membrane separator would pay off in its normal application is in logistics. Oxygen is cheap, but it is hard to handle. By having this device you can more or less forget handling pure oxygen. And you do not have to move all that steel back and forth to carry the gas; that is worthwhile.

UNIDENTIFIED PERSON: Is the output of that at a high enough pressure to feed a Haskel?

DR. VANN: No, it is not. They are set up to provide oxygen enriched air for patients?

UNIDENTIFIED PERSON: At one atmosphere. So you are going to have to have some kind of a compressor?

DR. VANN: Right.

MR. GALERNE: You need a tank and you need a compressor.

MR. STANTON: Morgan, you know we are putting in a system like you described in your talk. Did you modify or come up with any different types of filter packs on the compressor, or do you use a filter pack on it?

DR. WELLS: I think the only thing on there is an oil-moisture separator.

MR. STANTON: So you do not have any oil in the output gas.

DR. WELLS: We never find any oil; we find water. Are you talking about a charcoal filter?

MR. STANTON: Yes.

MR. GALERNE: One of the drawbacks of your system, I would say, is because it is not easy to change a mix. We are on a diving job, and today we are working at say 65 fsw, and tomorrow we are working at 80 feet. We do not use the same mixture or the same table. So we have to be able to change mixture once it is made without losing it. You cannot remove the gas, but you can add. You can add nitrogen to helium. Your system may not be precise enough to do that.

DR. WELLS: But your output is low pressure. You are doing all surface supplied diving?

MR. GALERNE: Yes. It is very sensitive to pressure, you know, because it is a very narrow range. A few percent more or less can make a big difference in the decompression time?

MR. RUTKOWSKI: You have to pick out a suitable way to mix. There are at least three different ways. You have weight, blending, and mixes by partial pressure. When we mix big quantities down at our facility, we mix by partial pressure. When we mix small quantities in our scuba or therapy cylinders we use the blending method.

DR. WELLS: This is probably not the most time-effective way to mix very large quantities of gas for storage. Then we can use pure oxygen and oil free air; that is what we are going to do in Seattle in our large "torpedo plants."

THE USE OF NITROX IN THE DIVING INDUSTRY

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Mr. Galerne is the owner and founder of International Underwater Contractors, a company that through Andre's efforts has always led the diving industry in innovations in the realm of decompression and creative use of gas mixtures. His extensive commercial experience in enriched air diving is of considerable interest and relevance to this Workshop.

ABSTRACT

Galerne, A. 1989. The use of Nitrox in the diving industry. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

As an innovative commercial diving company IUC has pioneered, among other things, the use of enriched air nitrox as a breathing gas for commercial divers. Starting in the 1950's the technology has been developed to include oxygen toxicity limits, decompression tables and procedures, and gas handling, mixing, and logistic techniques. Time savings are substantial in the range from 50 to 100 fsw. IUC has also used trimix in competition with heliox in the shallow heliox range, enjoying lower gas cost, better voice, shorter decompressions, and more comfortable breathing gas temperatures in comparison with heliox.

INTRODUCTION

My involvement with Nitrox diving tables goes back to the 1950's when, with Dr. Pierre Cabarrou, we were trying to find a way to increase the bottom time without jeopardizing the safety of the diver.

At that time the most important factor to the underwater construction contractor was bottom time because costs were inversely proportional to production time. Decompression time is costly because all activity stops to permit safe diver decompression. Using nitrox decompression tables, the number one problem is to determine what maximum partial pressure of oxygen a man can tolerate as a function of time and depth.

IUC NITROX METHODS

For example, we have designed a table with 1.8 ATA partial pressure of oxygen but not to be used for more than 30 minutes. For a longer period, we do not use more than 1.3 ATA PO_2. If you go to saturation you have to lower the PO_2 to 0.5 ATA to avoid oxygen toxicity (Figure 1).

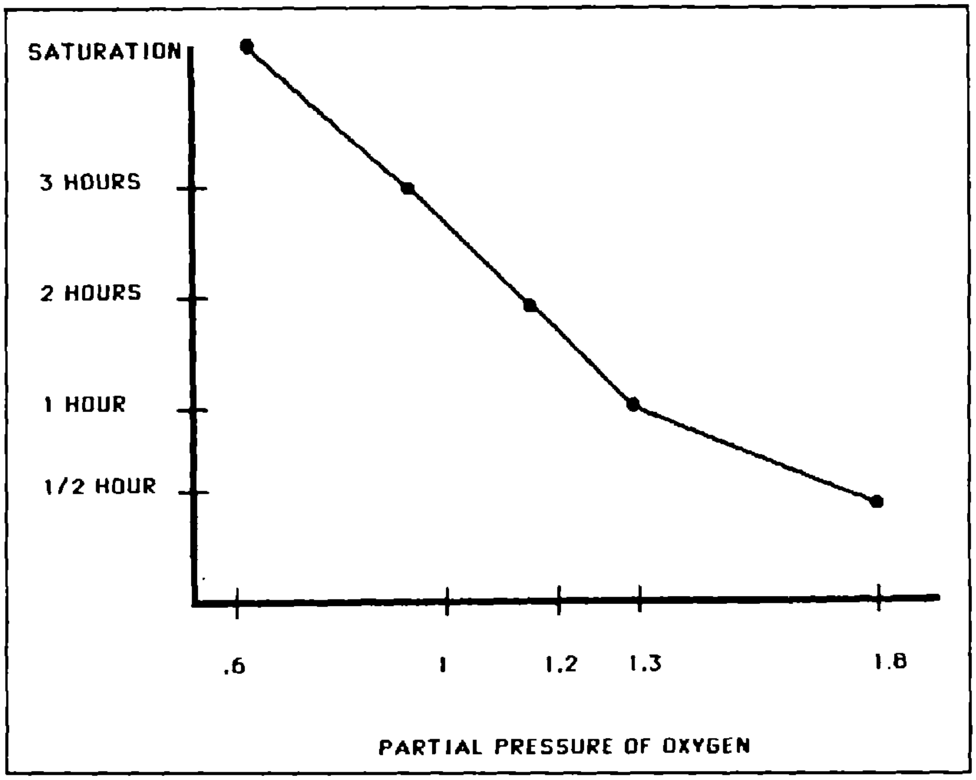

Figure 1. IUC oxygen limits. Line shows limit used for various exposure times.

The advantage of using a higher partial pressure of oxygen, means you decrease the partial pressure of nitrogen. By cutting the nitrogen, the intake load on the tissues is decreased and, in turn the decompression time is diminished.

A well calculated mixture in the range of 60-70 ft can produce dramatic results. For example, a mixture of 50% oxygen, 50 % nitrogen at 20 meters (66 ft - 3 ATA), corresponds to a partial pressure of oxygen of 1.5 ATA. But at 30 meters (100 ft - 4 ATA), the partial pressure will become 2 ATA with the same 50/50 mix, a level which is considered unhealthy for any underwater working condition. In fact, at that depth (100 ft) using the IUC tables for a 3 hour dive, you will use 26 % O_2 (PO_2 1.08 ATA) and a decompression time of 83 minutes. If you use the U S Navy Air table, for a 100 ft, 3 hour dive, decompression time is 203 minutes, which is practically 2.5 times longer.

We have used these tables very successfully, but they represent a little inconvenience. It is best to premix gas before the dive; this is more cumbersome than using a diving compressor, but the advantage of longer bottom time is definitely on the positive side.

If you use the U S Navy table for a two hour dive at 70 ft, decompression time of 53 minutes is required. Using nitrox, there is a 2 minute ascent time only and no decompression. In some cases, it not only increases productivity but may be the only way to be able to perform the work.

For example, this was made clear when we salvaged a barge called "Coastwise," in Norfolk, Va. This barge was filled with material which had to be pumped out before any attempt to raise it could be made. Previous attempts to salvage it by inexperienced salvors had broken the back of the barge in three places. The barge was in 66 ft of water with an average current of 6 knots which made diving possible only at slack times. The diver entered the wreck and, while protected from currents inside the wreck, was able to work for two hours. When he exited the barge, there was no question of decompressing so he jettisoned himself into the current and surfaced immediately. If the diver had been using air, he would have been limited to only 50 minutes bottom/work time. Using nitrox, his bottom production time more than doubled.

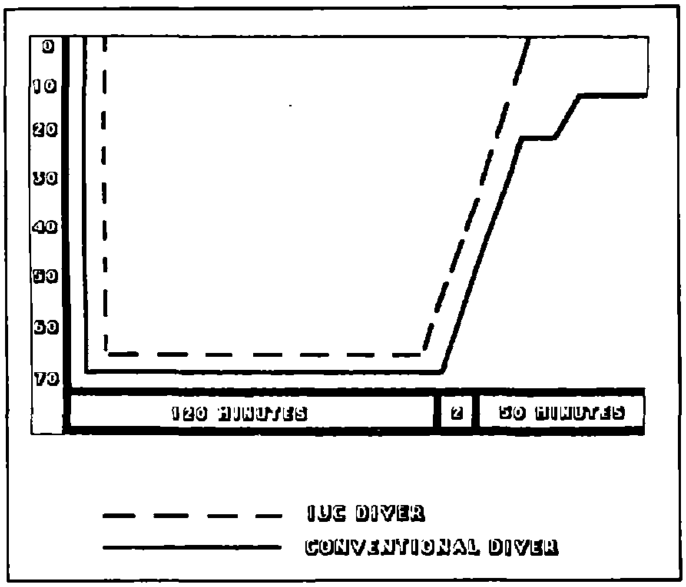

Figure 2. Time comparisons for IUC dives at 70 fsw. Air dives require 50 minutes longer decompression.

Nitrox can also be an advantage when diving at altitudes, where again lowering the partial pressure of nitrogen can have a significant effect on the length of decompression.

Because any mixture of oxygen above 27% is to be treated as pure oxygen, i.e., in the flash fire zone, use oil free compressor only. No diver hose or helmet that contained air from a regular compressor should be used with enriched air for fear of oil contamination. If these items must be used, they must be thoroughly cleaned.

The major difficulties for diving contractors in using these tables are logistics and diver training. The ideal solution is to educate the diver well enough to use gas mixing equipment, which allows the diving superintendent the opportunity to mix gas on the spot as a function of depth and sometimes as a function of time.

Our counterparts in the Gulf of Mexico have been very slow to use nitrox mixtures for practical reasons. Oil companies always pay for consumables, i.e., gas plus % for Overhead and Profit, so the local contractors had no incentive.

IUC, on the other hand, being more of a construction contractor, gas mixture was included as part of our lump sum price. So it was necessary to make very careful calculations between cost of mixture and production time. You can see that the optimum diving zone was between 40 and 100 ft. Below this depth, it is not cost effective to use mixed gas.

IUC TRIMIX

These tables then led us to develop trimix tables using helium as the third gas. The philosophy of trimix tables developed in the early 1960's was:

1. Decreased costs (air is enriched with oxygen and helium in relatively small quantities to arrive at correct compositions).

2. Less loss of body heat.

3. Less voice distortion.

4. Shorter decompression because trimix tables for bounce dives are faster than heliox tables.

NUMBER OF UPTD'S	CORRESPONDING DECREMENT IN VITAL CAPACITY, %
615	2
825	4
1035	6
1230	8
1425	10
1815	15
2190	20

Figure 3. Relationship between UPTD's and decrement in vital capacity. One UPTD (Unit Pulmonary Toxicity Dose) is equivalent to breathing oxygen at 1 ATA for 1 minute.

OXYGEN STRESS

To manage the exposure to oxygen we use a method developed at the University of Pennsylvania, which uses a unit called UPTD. One unit of UPTD (Unit Pulmonary Toxicity Dose) is equal to damage produced when breathing 100% oxygen at one atmosphere for one minute; i.e., if one breathes pure O_2 at 3 atmospheres for 40 minutes, the UPTD will be 120. The consequences of oxygen exposure in terms of UPTD are shown in Figure 3.

When working with high PO_2, you have to be very careful on two counts.

1. A too high PO_2 for too long can produce oxygen poisoning which in turn produces a tetanic-like seizure which is very dangerous when diving and it should be lowered immediately.

2. If one breathes a mixture above 0.5 PO_2 (air is only 0.21) long enough, lung damage can occur (Lorrain Smith effect) which will produce a decrease in vital capacity.

When making the decision to use high PO_2 tables, a different approach is to be taken. You have to start by making the decision as to what is the maximum acceptable decrease in the vital capacity of the diver. Normally, I will not go to a table which will decrease the vital capacity more than 10%, which corresponds to 1425 UPTD. If you take into account that there is the possibility of having a decompression problem and you expect to use Treatment Table 6 which accounts for 655 UPTD, you have to subtract 655 units from 1425, then your maximum units permissible for this dive are 770. Any dive using a mixture for a duration which will put you on higher units, will provoke decrease of vital capacity of the diver above acceptable limits.

This theory while largely accepted is, in my opinion, not infallible. I always recommend to my diving superintendents to watch carefully for signs of chest pain or cough. These symptoms will subside quickly with no lasting effects if the PO_2 is immediately lowered to a more acceptable limit.

To summarize this quick nitrox presentation. I must say that very often because of cost savings and/or safety of the diver, a nitrox mixture is your best bet.

However, my experience with nitrox or trimix dives leads me to believe that nitrogen per se is not narcotic but it will induce narcosis by its density, increasing the CO_2 buildup in the tissues and impairing oxygenation. I know this is not too "orthodox", but experiments that I have performed have led me to believe this. In fact, all my trimix tables are calculated to limit the amount of nitrogen in mixtures so that the density of the mixed gas is never greater than for a 100 fsw air dive.

Additional comments by Mr. Galerne:

I must say that I appreciate being invited to talk to you today. I am pleased to see Chris Lambertsen here because he is really the guy that has the information.

Let me speculate on why nitrox has not taken off. I have been involved with nitrox diving since 1957, 30 years ago. Dr. Pierce Cabarrou in France was a leading man in diving medicine at the time, and he taught me. I think we really mastered nitrox diving at that time. There are a few reasons why nitrox has not really taken off.

First of all, you need tremendous training for the divers. They have to know in depth the problems involved with nitrox; a little knowledge is very dangerous in this field. I doubt if you can teach somebody in 24 hours to dive with nitrox and believe that that man will survive too long. So the diving community, because of the trouble of training the diver to know what he is doing, is not using nitrox.

Another sort of a problem with a guy like me is that I was not ready to disclose to the competition how to do it. I am not paid to do that. I am paid to do my job and that is to make money for my company. So we have published very little about this. Now I am old enough now that I can talk. I think more people know it, so what I say to you now is not too much news, and that is all right.

Another thing, because the competitors did not have it they would "bad mouth" the mix, that it is no good, it is dangerous.

The insurance companies were on our backs saying we are trying to do something new there, and they did not like it. So it was not merely a question of the effectiveness of the nitrox. It was a practical way to do it.

So as I said, 30 years ago it was started in Europe. We now see our competitors doing it, so I can talk now. I hope what I had to say was some help.

Discussion following Mr. Galerne:

MR. RUTKOWSKI: Let me try to take a little bit of the scare out of some of the things you were saying. Pertaining to the oxygen, I think there was a little bit of confusion here. You were basically talking about two separate problems. One was about the oxygen in a compartment where the burning rate gets higher above 21%.

For instance, the Navy says that in recompression chambers or diving bells or whatever, any compartment, you should keep the oxygen fraction down below 25%. Well, in our compartments if it starts to get up around 22 or 23%, we then start venting to keep it low, because if you increase the oxygen percentage in a compartment by 5% you increase the burning rate by 34%. Of course, you have to have a source of ignition in that compartment to set that fire off. That is one problem.

Now, using oxygen in a closed circuit system, the Compressed Gas Association says with 40% or less you can have hydrocarbons, you can have petroleum base, and all of these other things, and you cannot have spontaneous combustion. When you get over 40% in your mixes going through these regulators in these systems and this piping and so on, then the possibility of spontaneous combustion or flashing is very high and you have got to have oxygen clean systems.

MR. GALERNE: That is what I said; when you open the bottle and have a surge of oxygen in the regulator, you have the hammer effect on the gas and the heat goes up. If you have a trace of oil, you can have a fire.

MR. RUTKOWSKI: Exactly; and if you have a spark of rust in stainless steel or something, that can act as an ignitor. I think this is important because this is going to be a transcript that the general public is going to read and we want them to know that oxygen 40% or less is not as dangerous as you made it out to be.

> [EDITOR'S NOTE: (See note in Discussion after Hamilton, page 27.) Mr. Rutkowski's statement that at oxygen percentages below 40% there is no fire danger in piping is misleading; we have been unable to document this value in current CGA literature, but it may have been used in the past. There is no hard line between "safe" and "unsafe" with regard to oxygen fires, and any enriched mixture with more oxygen than air should be handled using "oxygen" piping and cleaning procedures. RWH]

MR. GALERNE: Well, I would prefer to be scared and alive.

DR. CROSSON: On your graph, the 1.8, is that during decompression?

MR. GALERNE: No, that is in diving. If we make a quick dive for 30 minutes, we use 1.8 atm PO_2.

We use a "mix maker". It has two regulators and several gauges that show the different levels. It has a series of micro valves that gives you the possibility to try the mixture. I do not manufacture this equipment so I can talk about it.

It has a helium analyzer and two oxygen analyzers and a meter. Those systems work very well.

The last time we had a price on that it was $17,000. We have several of those. In my opinion they are very good to use; they are very safe.

The basic idea was from a new engineer that came with me on a job in Buffalo in 1963. We solved the problem of having to move a ton of steel to get a few pounds of gas.

I remember in my room in the motel that night we spent a few hours talking about how we could minimize that. We were doing a job in 265 feet of water, but we were ready to go into 600 feet. At that time I did not know how to go to the bottom of the lake. I had just come from Canada and we said, well, "We can do it." I was young, stupid, and was scared by nothing, so I said we can do a job like that.

Well, we used helium oxygen there, and it was a pain in the neck to have all of those gases--we did not know what depths. You take a gas mix that is good for 600 feet, but it is not maximized when we find the job was at 265 fsw.

So I was talking with this young man, a bright young engineer. I forgot his name. And finally he decided to do the job. You have a source of gas, a compressor or tank. If it is the tank, you have a variable input pressure to the mixer, and you want to have a constant input flow. It is difficult because you have a constant variation and the flow changes.

So the basic idea was to put a "micro" valve in the center between two constant regulated pressures. It uses "dome" regulators. The pressure in the first regulator is referenced to the pressure at the valve--the output pressure of a dome regulator is controlled by gas pressure. Another regulator controls the depth or output, so you can control the micro valve. You can control the flow exactly because it is between two constant pressures. It is very simple, and the system works very well.

He patented that. I suppose it is public now because that was 20 years ago or more. It works very well.

I would recommend for people that want to go to mixing to really look at that. It costs maybe $10,000 more, but it can save you a lot of money. Think about that for use on ships that cost millions; do not be cheap on that. Look at that carefully, because with that system you can cut back your gas storage and still be able to change your mixture. If you have the diver strength to do it, you never run out of mix.

You do not have the story you heard this morning, where the guy was adding oxygen every day and the mixture kept changing. I am sure a lot of divers may do that. It is easy to do. They do not think. The gas is expensive, so they do not dump it away.

If you have gas control/gas mixing equipment, you can save your gas and remix it with no loss.

UNIDENTIFIED PERSON: How much did you gas blender cost, Andre?

MR. GALERNE: I think the last price I heard was $17,000 plus the compressor if you use a compressor. You have to have a compressor for clean air. I must say that was years ago, I have not bought one recently. Business is going down which means there is no more need for divers in some cases, so we don't buy equipment. We have equipment for sale.

OXYGEN TOLERANCE IN NITROX DIVING

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Institute for Environmental Medicine
University of Pennsylvania Medical Center
Philadelphia, PA

Dr. Clark is and has been for over 20 years one of the leading investigators in working out the parameters for monitoring the development of oxygen toxicity. Since nitrox diving involves exposure to higher than normal levels of oxygen, a review of the physiology of oxygen tolerance is especially pertinent. He works at the Institute for Environmental Medicine at the University of Pennsylvania.

ABSTRACT

Clark JM. 1989. Oxygen tolerance in nitrox diving. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

Central nervous system tolerance to hyperoxic nitrogen-oxygen gas mixtures is required for the safe and effective use of enriched air nitrox mixtures in scientific and commercial diving operations. Human studies designed to provide such information are limited, but valid inferences can still be made based on data obtained from human exposures to 100% oxygen at rest and during working dives. Available data indicate that working dives using nitrox mixtures which involve exposures to oxygen partial pressures of 1.4 to 1.6 ATA for durations of 60 minutes or less impose a minimal risk of CNS oxygen toxicity but still provide important operational advantages. Risk of CNS toxicity is considerably increased during conditions that cause CO_2 buildup; possible causes of this could be suppression of hyperventilation during exercise, and the increased work of breathing dense gases. Some individuals have a reduced ventilatory response to exercise. Intermittent exposure improves oxygen tolerance.

INTRODUCTION

The use of hyperoxic nitrogen-oxygen gas mixtures in non-saturation diving provides an effective and practical means for reducing or eliminating both the required decompression obligation in any dive and the degree of inert gas narcosis in dives that are deep enough to cause prominent narcotic effects on air. Administration of hyperoxic gas mixtures or pure oxygen at shallow depths in the final stages of a dive also enhances the safety and efficiency of decompression by hastening the elimination of inert gas. However, these beneficial properties of hyperoxia must be employed within the limitations imposed by oxygen toxicity.

There is little available information that is ideally relevant to the definition of oxygen tolerance in man while breathing nitrox mixtures during working dives. Such information could be obtained only by exposing divers to the limits of oxygen tolerance in experiments that are designed to include appropriately wide ranges of nitrogen-oxygen gas mixtures under conditions that closely simulate operational working dives. The performance of these experiments would require years of effort and millions of dollars.

However, if the task is focused to include appraisal of a narrow range of nitrox mixtures that, although conservative with respect to oxygen exposure, would still provide important operational advantages, some valid inferences can now be made from available information. Nitrox dives involving exposures to oxygen partial pressures of 1.4 to 1.6 ATA (13 to 20 fsw) for durations of 60 minutes or less have been used advantageously in both scientific and commercial diving operations (Crosson, 1989; Wells, 1989; Galerne, 1989). This presentation assesses the degree of risk that significant effects of oxygen toxicity could occur during such exposures.

HUMAN TOLERANCE TO CONTINUOUS HYPEROXIA AT REST

In a multiyear, collaborative investigation of oxygen poisoning in normal men (Predictive Studies V), we have measured rates of development and recovery for oxygen-induced effects on multiple organ systems and functions (Lambertsen et al, 1987; Clark et al, 1987; Gelfand et al, 1987; Pisarello et al, 1987) (Table 1). The subjects breathed oxygen at rest in a dry chamber in order to define the greatest possible duration of oxygen tolerance. The measurements included brain electrical activity, visual function, auditory/vestibular function, muscle power, mental performance, pulmonary function, respiratory control, temperature regulation, cardiovascular function, renal and hepatic function, endocrine activity, and hematologic effects. Exposures were carried out over the range of oxygen pressures that are most useful in diving, therapy of gas-induced diseases, and general hyperbaric medicine.

Based on all that was known about oxygen tolerance in man at the outset of our study, maximum exposure durations were selected for each oxygen pressure to provide oxygen doses that would cause objective manifestations of oxygen toxicity and still allow complete recovery following exposure termination. The limits of continuous exposure duration were designated as 3.5 hours at 3.0 ATA, 6 hours at 2.5 ATA, 12 hours at 2.0 ATA, and 20 hours at 1.5 ATA. Neurologic, pulmonary, and cardiac criteria for exposure termination prior to the predetermined limits were established as part of a comprehensive system to ensure safety of the subjects.

The number of subjects studied at each oxygen pressure, average exposure durations, and ranges of exposures are summarized in Figure 1. The average durations of exposure and numbers of subjects studied at each pressure are 3.3 hours for 18 subjects at 3.0 ATA, 5.7 hours for 8 subjects at 2.5 ATA, 9.3 hours for a total of 30 subjects at 2.0 ATA, and 17.7 hours for 9 subjects at 1.5 ATA. A detailed discussion of the specific toxic effects that triggered each exposure termination is beyond the scope of this presentation, because overt manifestations of these effects varied in different individuals even at the same oxygen pressure.

Results observed at 1.5 ATA are described briefly, because this oxygen pressure lies directly within the range that was selected for appraisal. No symptoms were detectable until 8 hours of exposure when substernal discomfort, cough, and mild dyspnea were first experienced by some subjects. Lung volumes and flow rates were significantly decreased by 12 hours of oxygen breathing. Exposures were terminated at durations ranging from 16.8 to 19.0 hours for 8 of the 9 subjects on the basis of moderately severe pulmonary symptoms in conjunction with significant

Table 1. Predictive studies V: Measurements during continuous oxygen exposure in man. After Lambertsen et al, 1987.

Electroencephalography
- Clinical interpretation
- On-line spectral analysis
- Response to photic stimulation

Visual function
- Visual evoked cortical potential response
- Electroretinography (dark and light adapted)
- Fields (Rodenstock Perimeter)
- Acuity
- Accommodation
- Color vision

Auditory/vestibular function
- Audiometry (air conduction)
- High frequency audiometry
- Eye tracking, nystagmography
- Caloric stimulation, postural balance

Muscle power (skeletal, respiratory)

Performance (perceptual, cognitive, and psychomotor)

Pulmonary function
- Flow-volume loops
- Density dependent flow rates
- Closing volumes
- Peak inspiratory and expiratory pressures
- Airway resistance and conductance
- Frequency dependence of compliance
- Carbon monoxide diffusing capacity of lung
- Arterial blood gases and acidity (PCO_2, PO_2, pH)

Cellular and chemical composition of bronchoalveolar lavage fluid

Respiratory control/respiratory gas exchange

Temperature regulation

Cardiovascular function
- Electrocardiography
- Cardiac output, rate, stroke volume
- Mean thoracic impedance
- Blood pressure, systemic vascular resistance
- Orthostatic reflex responses

Renal function

Hepatic function

Endocrine activity, plasma hormone levels

Hematologic effects, blood electrolytic and protein composition deficits in pulmonary function. The remaining subject also developed pulmonary oxygen poisoning, but the immediate cause for ending his exposure at 17.7 hours was an increasing frequency of premature ventricular contractions. Only one subject had a detectable manifestation of CNS oxygen poisoning that presented as a reversible decrement in the electrical response of the dark-adapted retina to a light flash.

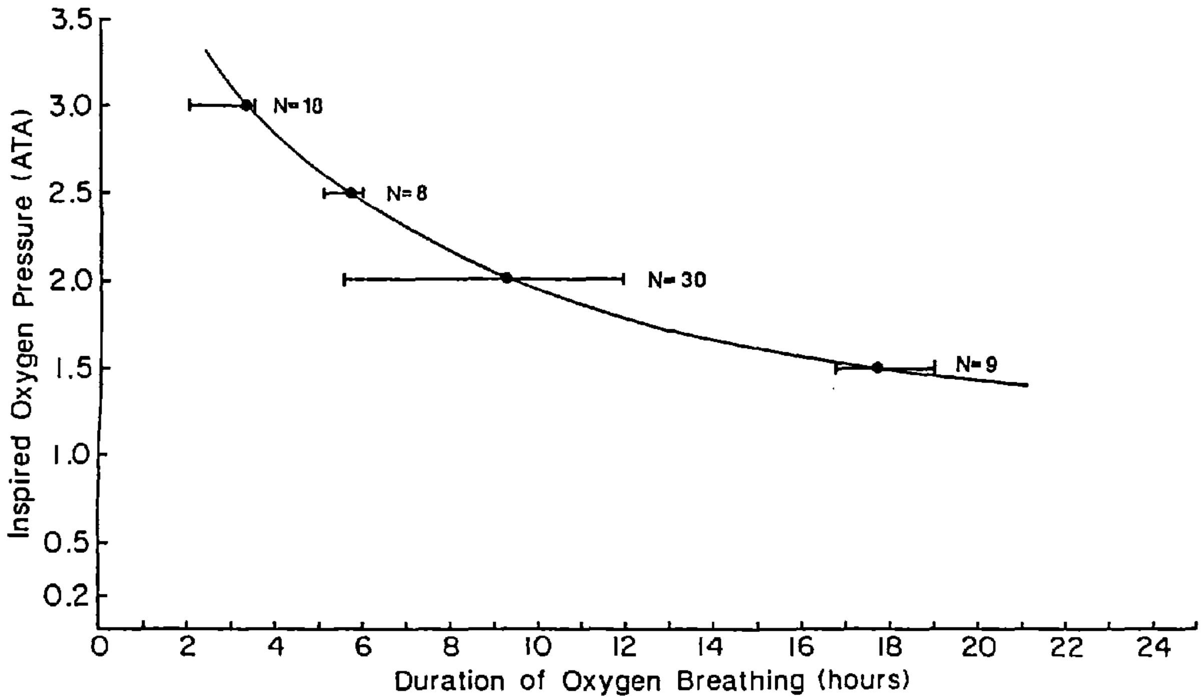

Figure 1. Human tolerance to continuous oxygen exposure at rest. Average exposure durations (points), ranges of exposure, and numbers of subjects studied at each pressure are indicated.

It is well known that exercise, especially when performed underwater, hastens the onset of CNS oxygen toxicity and also lowers the oxygen pressure threshold for its induction (Donald, 1947; Yarbrough et al, 1947; Butler and Thalmann, 1984; 1986). Although some aspects of oxygen tolerance data obtained in resting subjects cannot be applied directly to working divers, such information is relevant to oxygen exposure at rest for decompression or therapy, especially when these procedures are carried out in a hyperbaric chamber. Even allowing for an accelerated development of CNS oxygen poisoning during working exposures to oxygen pressures of 1.4 to 1.6 ATA, the data indicate that a 60-minute dive would still leave a substantial reserve of oxygen tolerance in the event that oxygen decompression or therapy were desirable or required.

CNS OXYGEN TOLERANCE IN WORKING DIVERS

Butler and Thalmann (1984; 1986) have recently published the results of a comprehensive re-evaluation of depth-time exposure limits for breathing pure oxygen during working dives. Work was performed in the prone position on an underwater pedal mode ergometer at simulated depths ranging from 20 to 50 fsw. The divers pedaled at a workload of 50 watts in alternating 6-min work, 4-min rest cycles, producing an average oxygen consumption of 1.3 liters/min. This exercise rate was designed to approximate that of a diver swimming at a rate of 0.8 knots.

Signs and symptoms of CNS oxygen poisoning that were used as indices of oxygen tolerance were assigned to one of three categories that were designated as convulsion, definite, or probable.

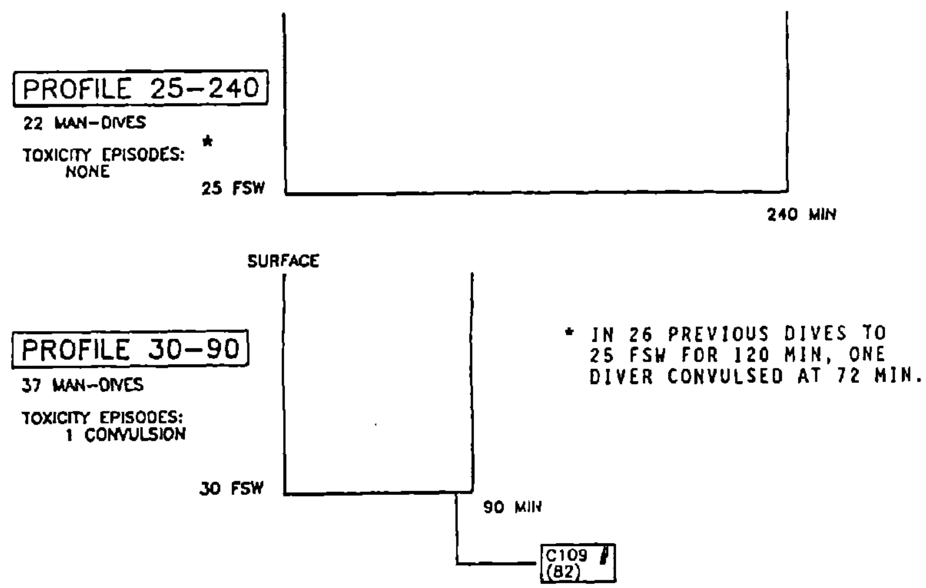

Figure 2. Central nervous system oxygen tolerance during working dives in man. Dive profiles included intermittent exercise during continuous oxygen exposures at 25 FSW and 30 FSW. Figure from Butler and Thalmann (1986). Data from 26 previous dives (Butler and Thalmann, 1984) also summarized on graph.

The convulsion category requires no further elaboration. Signs and symptoms that were almost certainly caused by oxygen toxicity, such as muscle twitching, aphasia, and visual disturbances, were classified as definite. Symptoms such as dizziness, tinnitus, numbness, tingling, nausea, and a feeling of dysphoria were classified as probable, because they were judged to be more equivocal than those placed in the definite category.

In a total of nearly 550 closed-circuit oxygen dives, Butler and Thalmann exposed more than 50 subjects to various combinations of depth and duration. The results of some of these exposures are summarized in Figure 2. In 37 90-minute dives at 30 fsw, only one toxicity episode occurred, but this was a convulsion at 82 minutes of exposure. At 25 fsw, there were no toxicity episodes in a total of 22 240-minute exposures. However, in a previous series of 26 120-minute exposures at the same depth, one diver convulsed at 72 minutes. This individual was later discovered to be one of three divers who were unusually susceptible to oxygen-induced seizures.

In order to investigate the effects of prolonged oxygen exposure at a relatively shallow depth on tolerance to a subsequent downward excursion, Butler and Thalmann exposed divers to oxygen at 20 fsw for 120 or 240 minutes prior to a deeper excursion. Water temperature was maintained at 21.7C or 12.8C. Results of the long shallow oxygen exposures with intermittent exercise are summarized in Table 2. There were no convulsions or definite toxicity episodes in a total of 161 dives. In 10 individual episodes that were classified as probable, one or more of the listed symptoms were experienced at the indicated exposure times. Some of the onset times were so short that oxygen toxicity has to be regarded as an unlikely cause of the associated symptoms.

Based on the data obtained from nearly 550 working dives, Butler and Thalmann have proposed new depth-time limits for closed-circuit oxygen diving. Their proposed limits, which will be published in the next revision of the U.S. Navy Diving Manual, are listed along with the old limits in Table 3. The previous limits are greatly extended at 20 and 25 fsw, with smaller extensions at greater depths. In recommending a duration of 240 minutes at 25 fsw, the investigators made a carefully considered decision to propose a limit that was not skewed by the fact that 1 of 48 dives ended in a convulsion at 72 minutes. They reasoned that shortening the exposure limit at 25 fsw to accommodate an isolated and anomalous toxicity episode would be unreasonably restrictive in light of the total body of experimental data.

Table 2. CNS oxygen tolerance during working dives. Data from Butler and Thalmann, 1986. (N = 53 Divers)

Dive Profile	No. Dives	Oxygen Toxicity Episodes (Probable)*
20 fsw x 120 min 21.7C	73	1 (5 min)**
20 fsw x 240 min 21.7C	38	4 (20,30,147,235 min)
20 fsw x 120 min 12.8C	25	2 (92,99 min)
20 fsw x 240 min 12.8C	25	3 (25,110,138 min)

*Symptoms: Dizziness, tinnitus, numbness, tingling, nausea, dysphoria
**Time of onset

OXYGEN TOLERANCE IN MIXED GAS DIVING

The depth-time limits established for closed circuit oxygen diving by Butler and Thalmann have been thoroughly tested under experimental conditions that closely simulate operational exposures. An equivalent empirical definition of human tolerance to oxygen partial pressures in mixed gas diving does not exist at present. An early attempt (Lanphier, 1955) to investigate oxygen tolerance in nitrox diving at the U.S. Navy Experimental Diving Unit was terminated when the initial subjects experienced unequivocal effects of CNS oxygen toxicity much more rapidly than was previously observed for pure oxygen diving. Rather than continue the exposures, the focus of investigation shifted

Table 3. New single-depth limits for closed-circuit oxygen diving. After Butler and Thalmann, 1986

Depth	Pressure	Previous limit	New limit
20 fsw	1.6 ATA	110 min	240 min
25 fsw	1.8 ATA	75 min	240 min
30 fsw	1.9 ATA	45 min	80 min
35 fsw	2.1 ATA	25 min	25 min
40 fsw	2.2 ATA	10 min	15 min
50 fsw	2.5 ATA	0	10 min

instead to an attempt to discover why the diver-subjects were so susceptible to CNS oxygen toxicity during working dives on nitrogen-oxygen mixtures.

Subsequent studies (Lanphier and Camporesi, 1982) at the Experimental Diving Unit and later in the same divers at the University of Pennsylvania revealed that these individuals characteristically had an inadequate ventilatory response to exercise and consequently developed a significant degree of hypercapnia (Figure 3). Even during exercise while breathing air at 1.0 ATA, their average end-tidal PCO_2 was over 47 mm Hg with individual values ranging up to 53 mm Hg. During exercise while breathing oxygen at 1.8 ATA, both average and individual values were still higher. When the divers exercised during exposure to the same oxygen pressure while breathing nitrox at an ambient pressure of 4.0 ATA, average end-tidal PCO_2 rose to 55 mm Hg, with the highest individual value at 70 mm Hg. The difference between end-tidal PCO_2 values for 100% oxygen at 1.8 ATA and 45% oxygen in nitrogen at 4.0 ATA was eliminated when helium was substituted for nitrogen. Overall, the data indicate that the extreme degree of hypercapnia associated with breathing nitrox at 4.0 ATA was caused by the cumulative effects of an inadequate ventilatory response to exercise, hyperoxic suppression of exercise hyperventilation, and increased work of breathing caused by increased gas density.

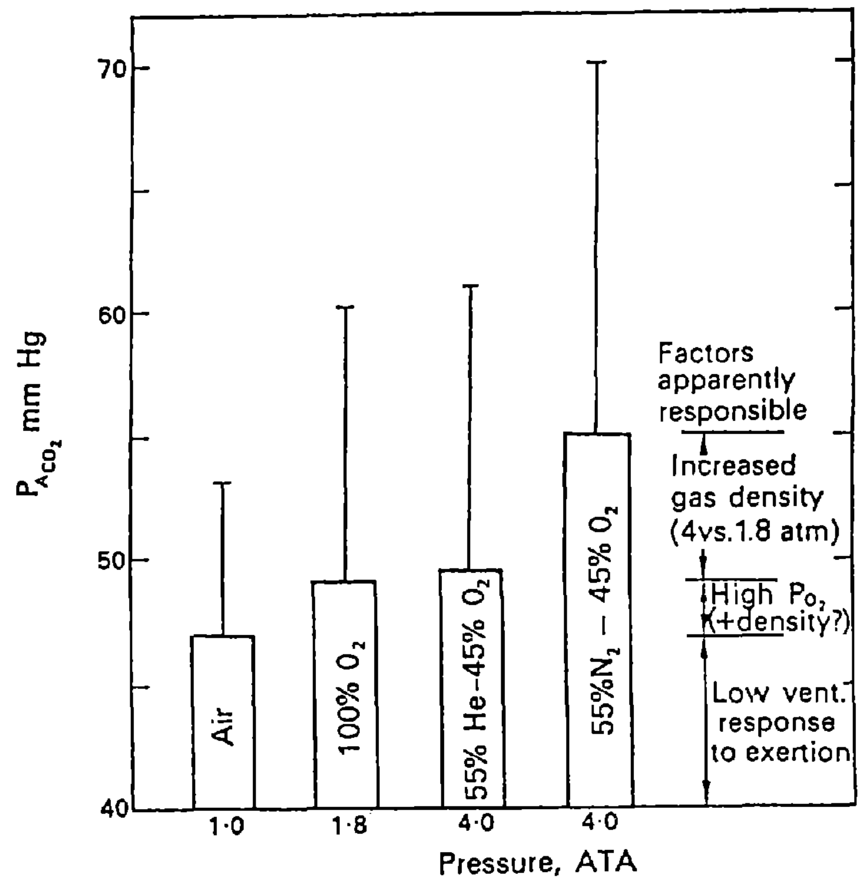

Figure 3. Carbon dioxide retention during exercise in divers who had early onset of CNS oxygen toxicity during mixed gas working dives. Ambient pressures of exposure are identified on the abscissa, and breathing gases are indicated within the bars that represent mean values of end-tidal PCO_2. The extended line above each mean value indicates the highest individual value obtained in each condition. Figure from Lanphier and Camporesi (1982).

The data shown in Figure 4 illustrate a physiological basis for the adverse effects of acute hypercapnia on CNS oxygen tolerance (Lambertsen, 1978). When oxygen is breathed at increased pressures, the associated elevation of brain PO_2 is limited by a concurrent reduction in brain blood flow and metabolic consumption of physically dissolved oxygen. Elevation of arterial PCO_2 by carbon

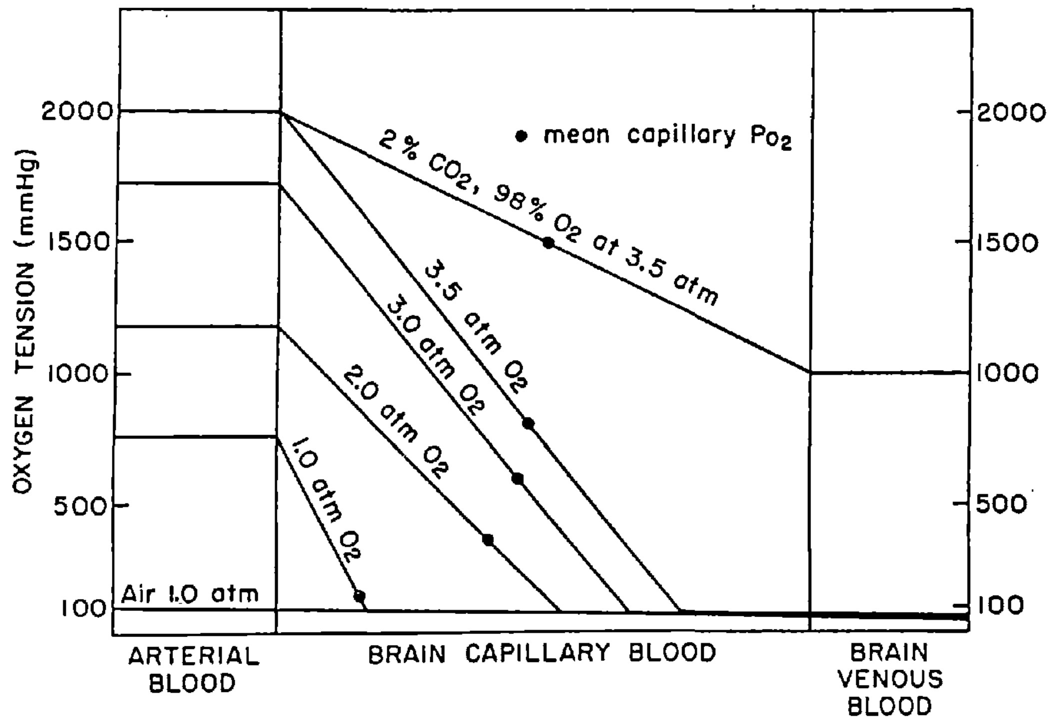

Figure 4. Effect of acute hypercapnia on brain oxygen tension. The graph shows average PO_2 values measured in arterial and internal jugular venous blood of normal men for several levels of inspired PO_2. It is assumed that oxygen is lost at a uniform rate along the entire length of brain capillaries. When capillary PO_2 falls to a level that allows hemoglobin to serve as a source of oxygen, the rate of fall in PO_2 changes abruptly. Induction of cerebral vasodilation by administration of 2% CO_2 in O_2 at 3.5 ATA dramatically increases brain oxygenation, as reflected by prominent increments in mean values of capillary and jugular venous PO_2. Numbers of subjects studied at inspired PO_2 levels of 0.2, 1.0, 2.0, 3.0, and 3.5 ATA are 8, 8, 6, 8, and 12, respectively. Figure from Lambertsen (1978).

dioxide administration or any other means causes cerebral vasodilation to deliver a higher brain dose of oxygen and hastens the onset of CNS oxygen poisoning.

Arterial PCO_2 elevations such as those found in the oxygen-sensitive divers are not usually found during exercise while breathing air. More typical responses to exercise are illustrated in Figure 5. The data shown are arterial PCO_2 measurements obtained in endurance-trained athletes who exercised at progressively increasing workloads during exposure to air or various levels of inspired PCO_2 (Clark et al, 1980). As exercise intensity was progressively increased from light to heavy, average arterial PCO_2 rose by about 1 mm Hg at low workloads and then decreased by about 5 mm Hg at the highest workload. Only when inspired PCO_2 was increased to 20 or 30 mm Hg did arterial PCO_2 approach the levels found in the exercising divers.

The occurrence of marked hypercapnia during exposure to an oxygen pressure of 1.8 ATA can certainly account for most, if not all, of the accelerated onset of CNS oxygen poisoning observed in the EDU divers breathing nitrox at 4.0 ATA. The physiological basis for this reduced ventilatory responsiveness to hypercapnia and exercise is not known, but later studies have confirmed the existence of this phenomenon in a subpopulation of divers (Lanphier and Camporesi, 1982). Whether this characteristic is inherent or acquired has not been established, but it is known that its retention is not dependent on current diving activity (Kerem et al, 1980). Regardless of its origin, the avoidance of hypercapnia during hyperoxic exposure should cause oxygen tolerance in nitrox diving to approach that found by Butler and Thalmann in closed-circuit oxygen diving.

EXTENSION OF OXYGEN TOLERANCE

The cumulative duration of exposure to an increased oxygen pressure that can be tolerated prior to the onset of toxic effects can be greatly extended by systematic alternation of hyperoxic and normoxic exposure periods. This practical and effective procedure takes advantage of the empirical observation that rates of recovery exceed rates of development for some effects of oxygen toxicity.

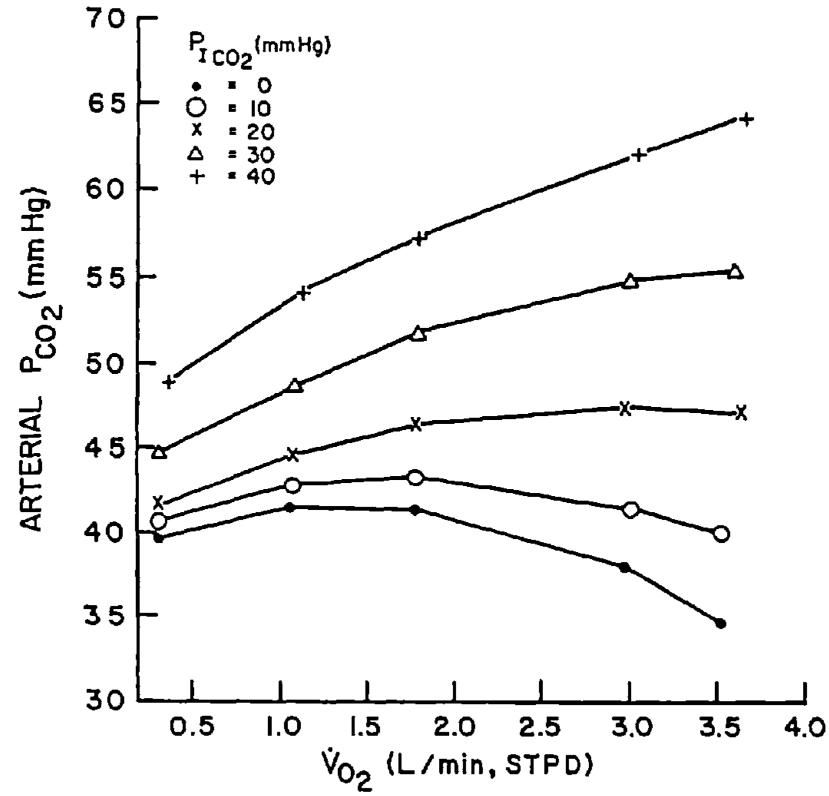

Figure 5. Arterial PCO_2 during exposure to combined exercise and hypercapnia. All data points are average values for 9 endurance-trained athletes. Resting measurements were obtained in each subject while sitting upright on a treadmill. He then stood and ran for 6 minutes at each of 4 sequential speeds. Arterial blood was sampled over a period of 1 minute during the 5th and 6th minutes of exercise. Figure from Clark et al (1980).

The cyclical development and reversal of toxic effects during alternating hyperoxic and normoxic exposure periods are illustrated hypothetically in Figure 6. The degree of CNS oxygen poisoning increases progressively during each period of oxygen exposure, but reverses quickly and completely during the intervening normoxic periods. On the other hand, other toxic effects, represented here by pulmonary toxicity, do not reverse completely during the normoxic periods and gradually intensify until they produce overt manifestations of oxygen poisoning.

Extensive animal investigation has shown that onset of convulsions and death can be greatly delayed by the use of appropriate intermittent exposure patterns (Clark and Lambertsen, 1971). It has also shown that the most effective intermittent exposure patterns must be individualized for specific oxygen pressures, as well as for specific organs and functions.

Hendricks et al (1977) have demonstrated that pulmonary oxygen tolerance in man can be effectively extended by intermittent exposure (Figure 7). At an ambient pressure of 2.0 ATA, 20-minute intervals of oxygen breathing were cycled with 5-minute intervals of normoxia. Using average change in vital capacity as an index of pulmonary oxygen poisoning, rate of decrease for 5 intermittently exposed subjects is compared with that for 11 other subjects who breathed oxygen

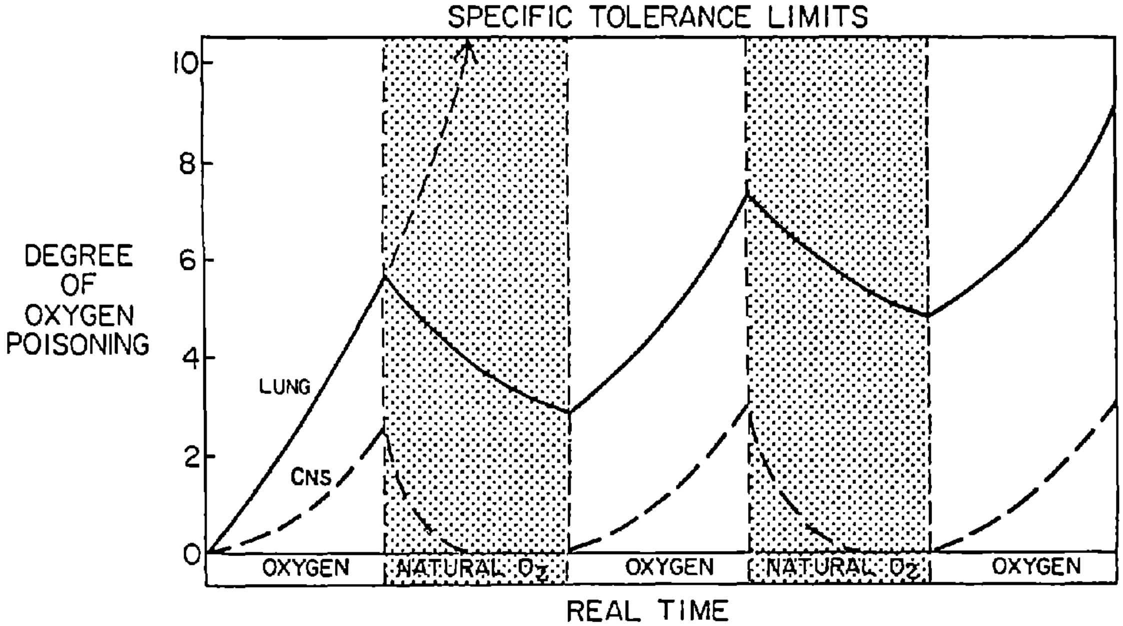

Figure 6. Conceptual basis for oxygen tolerance extension by alternating periods of hyperoxic and normoxic exposure. Normoxic recovery periods may involve reactivation of critical enzymes or restoration of antioxidant defenses. Concept proposed by Lambertsen (1955).

continuously at 2.0 ATA in a previous series of experiments (Clark and Lambertsen, 1971). An average 4% decrement in vital capacity occurred in 5 hours for continuous exposure, but required more than 12 hours during intermittent exposure. Thus, pulmonary oxygen tolerance was approximately doubled by the 20-minute hyperoxic, 5-minute normoxic pattern of intermittent exposure.

The principle of intermittent exposure as a means of protection against oxygen poisoning has been used extensively for many years as part of the now standard hyperbaric oxygen therapy schedules for decompression sickness, gas embolism, and other non-diving medical applications. Despite this widespread acceptance and use, the associated gains in oxygen tolerance have never been defined empirically. At the present time, extension of oxygen tolerance by intermittent exposure has been defined quantitatively only for the lung and only for one pattern of intermittent exposure at 2.0 ATA. Oxygen tolerance gains for other exposure patterns and organs must be determined across a wider range of pressures for maximal utilization of this effective principle.

SUMMARY AND CONCLUSIONS

Definition of central nervous system tolerance to hyperoxic nitrogen-oxygen gas mixtures is required for the safe and effective use of nitrox mixtures in scientific and commercial diving operations. In the absence of previous human studies designed to provide such information, valid inferences can still be made based on data obtained from human exposures to 100% oxygen at rest (Lambertsen et al, 1987; Clark et al, 1987; Gelfand et al, 1987; Pisarello et al, 1987; Donald, 1947; Yarbrough et al, 1947) and during working dives (Butler and Thalmann, 1984; 1987). Available

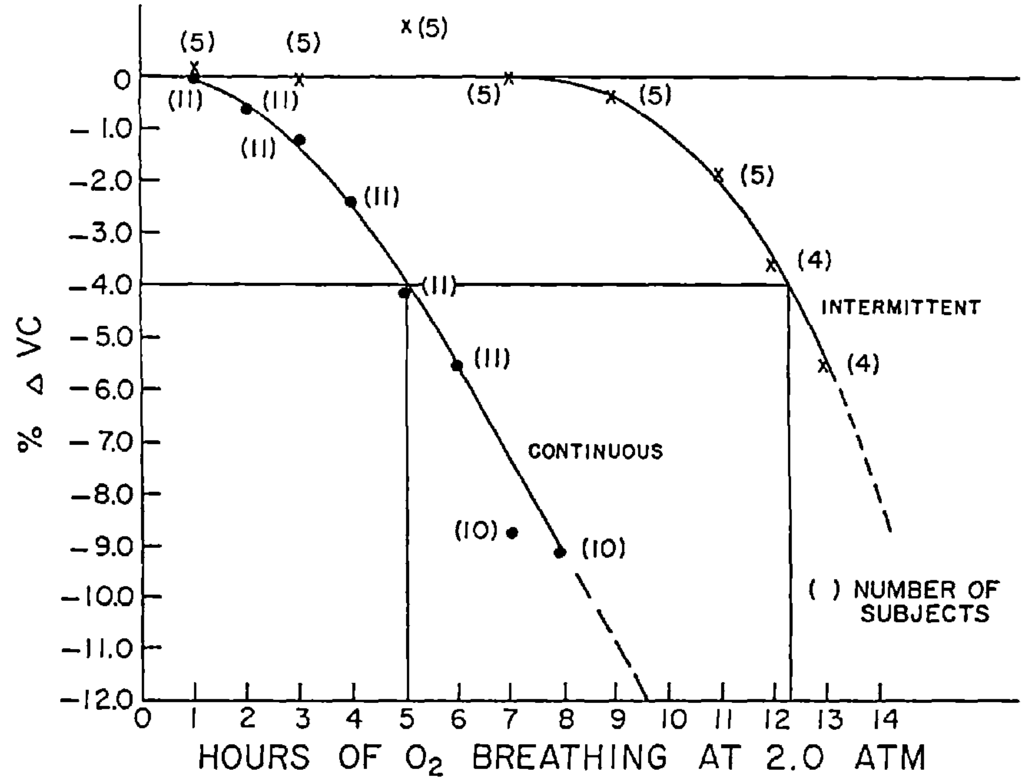

Figure 7. Extension of pulmonary oxygen tolerance in man. Numbers in parentheses indicate subjects for each average data point. Oxygen time for intermittent exposure represents the summation of oxygen exposure periods. Data for continuous exposure from Clark and Lambertsen (1971). Figure and intermittent exposure data from Hendricks et al (1977).

data indicate that working dives using nitrox mixtures which involve exposures to oxygen partial pressures of 1.4 to 1.6 ATA (13 to 20 fsw) for durations of 60 minutes or less impose a minimal risk of CNS oxygen toxicity, but still provide important operational advantages.

Risk of CNS oxygen toxicity during working dives is greatly increased by conditions that cause acute hypercapnia. The associated cerebral vasodilation delivers an increased oxygen dose to the brain and hastens the onset of convulsions. Possible causes of hypercapnia during nitrox diving include hyperoxic suppression of exercise hyperventilation and the increased work of breathing dense gases. It is also important to identify those members of the diving population who characteristically have an inadequate ventilatory response to exercise.

It will be possible to expand the recommended limits for CNS oxygen tolerance in nitrox diving as more information is obtained about mechanisms of neurologic oxygen toxicity and the detrimental influences of exercise during oxygen exposure. More effective use of alternating hyperoxic and normoxic exposure intervals as a practical means for extending oxygen tolerance will also be beneficial. Finally, the development of appropriate procedures for collecting and storing oxygen tolerance information obtained from nitrox diving operations for scientific or commercial purposes will provide an expanding data base for future recommendations.

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<u>Discussion following Dr. Clark</u>:

DR. HAMILTON: In Figure 7, is the oxygen exposure the same for the first two curves? That is, did the continuous oxygen and the intermittent oxygen have the same number of units at the time they intersected the 4% decrement, or did the intermittent exposure have less?

DR. CLARK: UPTDs are based on exposure, durational exposure to oxygen, and the intermittently exposed subjects had roughly twice the number of oxygen hours to produce the same effect. Allowing intermittent recovery in between each 20 minute dose, the oxygen exposure was actually more than double that which during continuous exposure produced the same change in vital capacity.

DR. HAMILTON: Were they getting the same exposure to oxygen per hour during that period?

DR. CLARK: The curve on the left is for continuous exposures. The curve on the right also done at 2 atmospheres was an intermittent exposure.

DR. HAMILTON: But it is over a longer time.

DR. CLARK: Yes, had a greater duration. The cumulative duration of oxygen exposure was double in the intermittently exposed subjects. That is the big advantage of intermittency. Let us say in a 24 hour period one could get more cumulative exposure to oxygen intermittently than during continuous exposure, allowing a certain degree of toxicity to develop.

DR. HAMILTON: Let me rephrase my question. What I am trying to find out is if the total number of units that one can take would be increased if one took it intermittently.

DR. CLARK: In the calculation of UPTDs it is assumed there is no recovery. We know that is wrong, there is recovery. It was done intentionally that way because when that was first done, we did not know a lot about rate of recovery. We know more now, but still not that much. Everybody knows there is reversal of toxicity.

The UPTD calculation does not take that into account. But the empirical observation is that when you expose these subjects intermittently, they do recover; and given a duration of exposure to produce a certain change in vital capacity--and this is in the case of 4% decrease--you could get double the number of oxygen hours.

Now, if you assume that there was no reversal, then that would be twice the number of UPTD units but there was, in fact, reversal in between.

DR. HAMILTON: But is this double the number of hours at the same atmospheres?

DR. CLARK: Yes, at 2 atmospheres.

CAPT HARVEY: Does the presence of an inert gas at any given partial pressure of oxygen affect either the development rate or the recovery rate from oxygen toxicity? I know a lot of the work is done on pure oxygen but what does the presence of inert gas do?

DR. CLARK: Very little of that has been done in man. If you look at animal data the studies are contradictory. You can almost make any conclusion you want. I think it is probably because there are different conditions and we do not understand them.

Early observations starting with the time of Paul Bert seemed to indicate that a survival time or time to convulsions was effective with PO_2. Two atmospheres of pure oxygen would give you the same thing as 4 atmospheres of 50% oxygen.

Since that time there have been some studies which indicate that the presence of inert gas has an effect. One study where there is a large quantity, like 15 or 20 atm of inert gas on top of oxygen actually enhances the toxicity, the animals die earlier.

There are other studies which indicate that smaller amounts of inert gas, again in animals, tend to have a protective influence. So it is somewhat contradictory.

All of these exposures are survival types of things, much, much longer than we are talking about in the divers. The effects of inert gas on CNS toxicity has been misidentified.

There is one study in animals done by Bitterman at higher levels of oxygen, 4 to 6 atmospheres, where there did appear to be an effect of inert gas which initially at lower pressures hastened the onset of seizures and later let them come back again. So it is a pretty complex thing.

The animal studies are really done at a whole different range. They are much longer exposures and much, much more severe.

DR. CROSSON: What I am hearing is there may or may not be an effect of inert gas. Then what is your feeling when from an operational standpoint we go to the limits? For instance, the mixed gas PO_2 limit at 1.6 atm is 30 minutes; then what is the time limit for 1.6 atm PO_2 in pure oxygen?

DR. CLARK: Table 3 is from the NOAA Diving Manual, where the two recommendations were published together intentionally to show the contradictions.

Now, remember the old limits have been greatly extended by Butler and Thalmann. But the old limits indicate that, for example, at 1.6 atm, 20 fsw, the allowable exposure for normal operations is 110 minutes. At 1.6 atm breathing mixed gas the allowable exposure time is only 30 minutes.

That was based, as far as I know, on Lanphier's observations where quite unexpectedly they found during mixed gas exposures with their subjects that they convulsed more rapidly or had things like twitching and so on. That is the group of divers I am talking about. Those are the people that have gross retention of carbon dioxide which is going to push them in that direction. Whether the CO_2 caused all of that, we do not know.

DR. CROSSON: Here we are looking at 1.6 and 110 minutes or at 30 minutes, based on evidence that may or may not be conclusive. I guess I am just trying to figure from an operational standpoint what I should use? What are my guidelines?

CAPT HARVEY: The reason they are different is because they were developed at different times. One group was assigned the tolerance curve for the Emmerson rebreather, another was assigned the job of developing helium tables using so much oxygen. So different people arrived at different conclusions, and thus in the manual in different sections you will find different oxygen curves.

USN are trying to bring those together, and I expect that the next issue of the diving manual will be more consistent. But the work of going back and redoing the tables to meet the common oxygen tolerance set of curves would be prohibitive right at this point. So they decided just to live with different oxygen levels in the different sections.

DR. VANN: Isn't the argument there that when you are diving with mixed gas you are at a higher risk so your duration is less?

CAPT HARVEY: That was part of the reason the Navy were willing to tolerate different levels. There are quite a few things that all bore on what curves they arrived at for different tables.

DR. LAMBERTSEN: What you are dealing with is oxygen breathing at low pressures where density does not come into it very much. But oxygen is a poison and oxygen poisoning is happening. It is not happening just in the lungs. Andre said it was happening in the adrenal glands, and so forth.

At any rate, you have to decide what you mean by oxygen poisoning. You know poisoning is happening. Where is it happening? The central nervous system and the pulmonary system.

Then suppose you say, all right, we are going to exercise and breathe pure oxygen. Oxygen poisoning is going to happen. Where is it going to happen? You are going to convulse sooner, but that does not mean that the lungs are going to convulse sooner, does it? The lungs may not be poisoned faster in exercise because their dose is not changing in exercise. In the brain the dose is changing in exercise. So the brain may be getting a higher dose. It is not necessarily more sensitive. It may be getting a higher dose in exercise, especially if something makes CO_2 pile up. The CO_2 is probably not going to hurt the lungs any. So you have to keep the kind of poisoning in mind.

Keep those in mind, instead of sensitivity, and then these things begin to fall together a little bit. Then you can say, suppose I go on to an inert gas. The question is, what does an inert gas do? Jim was right. Nobody has resolved it at all, but you can take the inert gas in a cell and consider oxygen poisoning in that same cell, and probably the inert gas does not do anything at all to oxygen poisoning. But if you put the inert gas in the lung and foul up the breathing and then cause CO_2 to pile up through density and other effects, then in that cell it does change. And you may think that inert gas at that cell is making that poisoning happen differently. It is not at all. It is happening somewhere else, in the lungs. But the lung is getting along just fine. It is not in the cell that it is happening. Inert gas is working here in the lung, but the result is in the cell. Put that all together and it begins to fall into a pattern.

If you keep saying what is inert gas doing here in the cell, that is a separate topic. You have to study that only by examining it in the cell and not in the whole mechanism.

This was a long speech but it all connects together if you can see the patterns.

MR. GALERNE: I think you can have the problem with equipment. If your equipment does not function very well, you can have increase of CO_2 rapidly.

DR. LAMBERTSEN: Now you can go to Dudley's question. Now we can talk about his question because now we can get practical. Since these things are all going on, practically, what you do is move over and let them all happen, because you are not going to change them. Move over on the safe side and allow some room to work. If people insist upon underbreathing, it is going to be their tough luck, or maybe you have to train them not to underbreathe, or something like that.

Just like decompression, you have to move over and encompass the problems and push them aside, rather than try and keep all of the problems and then see what you can do about them while you still have them.

CAPT HARVEY: The equipment you use is important in terms of what regulator. That is, if you use regulators that can ventilate very, very well, you may have a different problem than if you were using different ones. People vary in what they have been able to afford and what they have bought.

All of these from the other factors we have talked about are going to come together, and would make me--in your situation--tend to use a more conservative oxygen approach rather than try and optimize. I would tend to use the more conservative oxygen figures.

DR. CROSSON: Just to follow this up a little bit more, I agree for the more conservative, but can we truly accept that being a valid parameter?

DR. CLARK: Let me respond to Claude's comment. I would agree that since there are a lot of things that we do not know, that it would be inappropriate to assume that it is only PO_2 related, to say that during mixed gas exposure we can use the new more liberal limits proposed by Butler and Thalmann for pure oxygen. I think that would be going too far. We should be more conservative than that, but I do not think we should go as far as the most conservative limits. I think that is unduly conservative.

We already know from experience, and people have been saying here all day that they have been doing 1.4 and 1.5 atmospheres for up to an hour. I think it would be very useful in this operational experience, commercial or scientific, wherever it is occurring, if these people would start collecting these observations, because in effect they are experiments. All of those are experiments, and if you have negative exposures for those periods of time and you accumulate a number of exposures that have no effect, that is useful information. Then you can move over that hour or something like that, and accumulate it that way.

DR. CROSSON: Recently I had a chance to talk to Jean-Pierre Imbert of Comex, and when we talked about the type of operation I had been involved in before and we are looking at here, for lack of a better term in a sense he chastised me for going as low as 1.4 atm. He said it is 1.6 for a couple or three hours. They use it extensively. I cannot believe the physiology of Europeans is all that different.

DR. CLARK: I think if they are doing those exposures in large numbers of divers, that it would be useful to the public; they should let the rest of us see that, because it is very useful information.

MR. GALERNE: I do not know of any accident of oxygen at the job site. In my organization there is none. I do not recall oxygen toxicity on the job site.

You are right, Comex uses pretty high levels.

DR. LAMBERTSEN: Dudley, remember, you are dealing with two different organizations and two different types of divers. You as a scientific diving organization have to have a different set of standards than when someone has a whole system of control over the diver and is able to take care of and solve the problem if it develops, as opposed to someone wondering around the reef with a buddy on the boat. You just have to be willing to be more conservative without feeling ashamed of yourself. Isn't that right?

MR. GALERNE: Yes.

DR. LAMBERTSEN: That is all I am saying. Make your own local decision.

DR. WELLS: Regarding that thing for breathing pure oxygen. When it says pure, you have to take that in quotes, because in some oxygen rebreathers you do not breathe pure oxygen. The older studies with the Emmerson rigs say that the guys are running around with about 80% oxygen in the oxygen rebreather. I do not know about Thalmann's data.

DR. CLARK: They measured it and they looked at it carefully. When It started to fall down towards 95% they changed the rig. They kept it above 95%.

DR. WELLS: See, there is some correction needed. I am not sure of the true origin of it, but with the oxygen rebreather you are not breathing pure oxygen. On a demand system you are. I think he may have pointed out that it depends a lot on the nature of the equipment.

That is one reason for a difference, in addition to some of the others that you have mentioned. You mentioned Ed Lanphier's work a number of years ago on CNS O_2 toxicity, I think, in which he indicated that PO_2 is not straight PO_2, that the presence of the inert gas hastened the onset of CNS oxygen toxicity.

DR. CLARK: Or the development of the hypercapnia in divers.

DR. WELLS: I guess what I am saying is that there is more than one reason to suspect that oxygen is not just oxygen with respect to oxygen toxicity if there is CO_2 or if there is an inert gas present.

DR. CROSSON: I can fully appreciate that. I guess in my mind it is just a drastic difference in what is being done elsewhere. I am just looking for a logical or rational limit. It seems like there are varying limits.

DR. CLARK: In the Lanphier exposures, and there are only two, given the presence of the degree of hypercapnia that they later established occurred, you just cannot say there is an inert gas effect, at least from those circumstances.

DR. WELLS: You can not say there is not, either.

DR. CLARK: Agreed.

MR. FLAKE: I have a question of an operational nature. Say Harbor Branch were to go into a diving situation off of one of our vessels simultaneously with a submersible operation. The equipment that we have on hand right now for a treatment would include a chamber with a depth capability of approximately 190 fsw, air, oxygen, and we normally carry on the ships a mixture of 10% O_2, 90% He.

It is not extremely likely, but if you were treating somebody that had done a series of repetitive dives on nitrox, and if you were to have an incident during treatment, the worst possible case, and you were to have a situation where somebody was having a severe problem with oxygen toxicity in the chamber, what are the options?

Obviously if the guy is on air in the chamber, you cannot easily lower the PO_2. A possible way you could do that would be to flush the chamber with the 90-10 heliox mix, but somehow that seems a little risky. What would your protocol be in a case like that?

DR. CLARK: Are you saying that this diver had an exposure to some increased oxygen before?

MR. FLAKE: Yes. Let us say he has done a series of nitrox dives and you have chosen to treat him on a Table 6 and you get him in the chamber and now you have some kind of a severe oxygen reaction. The guy is on air in the chamber. What are our options?

DR. CLARK: Presumably he had the hit while he was on oxygen. First of all you could have him breathe chamber air and that is probably going to cure the problem.

MR. FLAKE: My question is, you put him in the chamber for a decompression problem. While he is in the chamber he has a CNS hit. I do not know how likely that would be.

DR. CLARK: Not very likely. What is the oxygen level in the chamber? What depth are we talking about?

MR. FLAKE: 160 fsw.

DR. CLARK: On air.

MR. FLAKE: That is pretty high.

DR. CLARK: Not very high for a resting man in the dry. He is not likely to have a CNS problem with that level of oxygen.

MR. FLAKE: Even if he is carrying levels of pulmonary toxicity?

DR. CLARK: He may eventually develop pulmonary toxicity.

MR. FLAKE: Now, the pulmonary toxicity you could basically ignore and just continue the treatment?

DR. CLARK: Within limits.

MR. FLAKE: Your only other choice would be to flush the chamber and bring him out.

MR. GALERNE: Do not breathe any more oxygen, and prepare yourself for saturation. You go lower and lower. No more oxygen.

MR. FLAKE: Would you recommend in a situation like this that if you had a mixture of helium and 10% oxygen on hand to ventilate the chamber and come out on saturation with that? Would that be viable?

MR. GALERNE: If you have equipment to do saturation, yes.

CAPT HARVEY: If you have a large load of nitrogen in your system and you try to treat with helium, you may run into a counterdiffusion problem. You have a person in a chamber with large undefined loads of nitrogen, and you now start feeding him helium as a treatment gas; depending on the depth you may well have a supersaturation or counterdiffusion problem. You can get around that by overpressurizing.

MR. FLAKE: In this particular case the chamber is good to 190 fsw.

CAPT HARVEY: It is hard to make a rule that it would be absolutely safe to switch to helium, because you do not know the load of nitrogen except to figure out what is probable. I would tend to steer away from using helium in that mode.

MR. FLAKE: In other words, basically reduce the oxygen as much as you can, and if you have a "metabolic" feed, turn that off and continue the decompression treatment and try to ignore the symptoms?

CAPT HARVEY: Using air.

MR. GALERNE: You would not switch to pure helium completely. You could go to tri-mix.

MR. FLAKE: You complicate it.

MR. GALERNE: Well, at that time you have to think seriously of what you are doing.

CAPT HARVEY: We were able at 99 fsw with a person saturated on nitrogen to produce decompression sickness by switching to heliox. That was a very quick shift. Actually on that particular experiment we flushed the chamber gas and had them take suits off. So it was a sudden shift.

MR. GALERNE: On tri-mix dives we go from depths of 120 fsw and there we switch and we do not have too much of a problem.

When we are on board a vessel for deep diving and we have nitrogen and oxygen mixtures, with a treatment it is better to use air than heliox. We use nitrox in deep water.

When we go to great depths we practically never have long term decompression sickness, because we treat in a few minutes following the symptoms.

MR. FLAKE: Then you come back on satuation?

MR. GALERNE: And then come back on satuation because we are equipped for it.

The problem is that 99% of boats are not equipped for satuation. The satuation chamber is pretty messy; you have to pull the bucket out and everything.

MR. RUTKOWSKI: You proposed a couple of hypothetical problems that are very improbable.

MR. FLAKE: Apparently that is what I am hearing.

MR. RUTKOWSKI: You got into a very complicated situation there that you have to know a lot about, and is going to require more knowledge than we can arrange here in the next hour.

MR. FLAKE: Obviously in a situation like that the first thing we would do is call for help?

MR. GALERNE: We call when we have a problem.

MR. FLAKE: You might have a problem if you had CNS oxygen symptoms to be able to tell the difference between the CNS problem and normal decompression sickness. You can have a diagnosis problem to start with.

DR. HAMILTON: To change to another topic, I made the proposition earlier that we should throw away the USN mixed gas oxygen limits below the CNS limits of about 1.4 atm, and use only the long duration daily dose dealing with toxicity in the range 1.4 and below.

Does anybody have any objection to that?

Dr. Lambertsen, you warned me not to ask a question that had a yes or no answer, but I am doing it.

DR. LAMBERTSEN: Bill, will you throw away the misuse of the term "chronic" which you used this morning in your paper. You said we have CNS poisoning and chronic oxygen poisoning, and you meant pulmonary. You said you meant pulmonary but you are going to call it chronic, okay.

Now, pulmonary oxygen poisoning is acute oxygen poisoning. If it is acute, do not call it chronic. That relates to what you are doing. I am not going to let you talk about throwing away the limits until you get your words straight. Chronic oxygen poisoning usually refers to a scarring of the lungs generated by patients that have been treated extensively. You do not want to equate any acutely generated diving oxygen poisoning as chronic, because that is a bad word. That means it is going to be there forever, and that is not the case with diving oxygen toxicity.

DR. HAMILTON: Are you saying that the fact that it takes many hours rather than a few minutes to develop, it is still "acute?"

DR. LAMBERTSEN: Prolonged exposure is chronic.

DR. HAMILTON: The fact that it involves more than the lung is the reason why we chose the word chronic. "Pulmonary" does not say enough. But you made your point.

DR. LAMBERTSEN: You want to now remember that you just asked a question, but if you get an answer to that question, that would reinforce an error in the record there.

DR. HAMILTON: But you straightened out a different issue. What about the question I asked?

Well, do I interpret the silence to mean no objection?

DR. CLARK: What are you saying?

DR. HAMILTON: We worked out a procedure during the Repex Project for controlling the long duration non-CNS oxygen toxicity (which I am not allowed to call chronic any more but which is more than pulmonary, although pulmonary is the most obvious part of it; we can use that term for this discussion). We found that one can control that on a multi-day basis. We are concerned about managing it on a day in and day out basis, where you have an operation that is going on for days or weeks at a time. We were concerned about it with nitrox saturation-excursion diving, where you can get an excessive daily O_2 dose.

If you look at this (Figure 2 in the Hamilton paper) in terms of either an average daily dose or a total dose for a given mission duration, then that is really all you need to worry about.

You do not need to worry about the PO_2 at any given time as long as the total units for the day do not exceed this pattern (and you stay below the CNS limits).

Let me try to tell you how we got these numbers. It answers a question that Jim Clark asked me earlier. These numbers are ones that we put together with the best data we had. They are not cast in concrete by any means, but they are the best guess we can come up with as to what you can tolerate on a day by day basis.

In a lot of decompressions of people in deep heliox bounce dives for Ocean Systems we gave them a lot of oxygen in the chamber after the initial dive. We did a number of these exposures, and we often exceeded a CPTD of 850 units. That is a lot, but we decided that for a one day, one shot exposure where tomorrow you are off, you go to the movies, a person can take that dose and still have enough to stand a treatment. It is quite consistent with the numbers Andre mentioned. He said 1425 units would be the limit that he would want to go to. After 850 units you could give a person a Table 6 and you would be only a little bit above that, even if you hit your Table 6 at the very end of your working day. So for one lone day we came up with 850 units, and we are comfortable with that.

Now, at the other end the daily dose is in the neighborhood of 300, where the curve straightens out. The best data we have is two data points, two subjects in New London during SHAD II. We are severely lacking in data at that end of the picture and this could be wrong, but a lot of other things converge on this.

We are concerned, for example, with tunnel workers who will breathe oxygen during decompression on a day in and day out basis. Divers do not usually work like that, but some people do.

For the middle of the range we used some data from Walter Sterk, a doctor and physiologist who works for a Dutch diving company. He let divers do their daily work, and then he put them in the chamber and gave them additional oxygen until the total for the day was 615 units (CPTD). He was testing that value as a daily dose on a day-by-day basis. He gave it to them for two weeks.

There were no real symptoms during the week, but during the weekend after the first week they all complained of lack of aerobic capacity, inability to participate in sports, fatigue, and a lot of vague, uneasy problems and things, during the off time. They then went back to work, followed each day by the chamber, and by the end of the second week they had had enough and the experiment was terminated.

Sterk started another run at 800 units a day, but did not even finish the week on that one because it turned out to be too much. Sterk has done a number of other similar things, and using his data we rounded out the curve in the center. Again, we have to fill the curve and smooth it over with good guesses because we do not have enough data for every single moment of it. But using that approach and putting these things together, we have come up with a pattern.

One problem is that you have to know how long your mission is going to be. If you plan a two day mission which allows you to burn up 1400 units, but then at the end of the second day you realize that you have to work another day then you really only have 460 units for that day.

In other words, you do not have 620 the third day, you have only the difference between the second and the third day, because you have used up some of your third day in the first two days.

At any rate, using the lower curve as the average daily dose and the upper curve as the cumulative dose, if you keep your people under the upper curve we presume that it does not matter too much in what order they get it.

Remember I am talking about these exposures all at a level below the CNS limit of 1.5 or 1.6 atm. So here we are not concerned about the rapid exposures at 2 atm and above.

UNIDENTIFIED PERSON: What is your question?

DR. HAMILTON: Does anyone have any problems with this?

DR. CLARK: There is a dose of pulmonary toxicity that will leave no residual the next day. There will be nothing, no accumulation.

DR. HAMILTON: This is not an absolutely and totally meaningless exposure. This is an operational exposure. We estimated as we put this thing together that one person out of a group of three or four people might feel a little chest tightness or other very mild symptoms, and that was exactly what we found in Repex (with exposures somewhat above the line). Actually, we think we hit it pretty well. We did not expect to find no feelings in anybody. We really were shooting for what is considered an "operational" limit. You can get chest tightness in your divers when you work them through a couple of long days or a long hard dive. You do not see this very much in the normal routine, although if you get seriously into creative types of enriched air diving you might accumulate doses in this level if you do it on a daily basis. In fact, the issue is perhaps moot for this Workshop, but it is an important thing for other situations where you have a lot of oxygen exposure.

DR. LAMBERTSEN: He is asking a question, and I guess the general question is, "Is there anything wrong with the concept?" It certainly seems like a perfectly sensible operational concept.

To tie it back into what Jim Clark said, if the exposure is not operational such as perhaps the use of HBO therapy instead of diving, then the other concept can be made use of, namely that you do not want to have any accumulative thing at all. So there are two concepts.

The third element is, if you ignore the numbers but consider the concept, it sounds all right. If the numbers are a little bit off, they can be changed with time. So you do not have to worry about exact numbers.

DR. HAMILTON: I am not standing strongly behind the numbers. I am just showing you what we got, saying that it is a start.

DR. LAMBERTSEN: You then go on with the intermittent studies in man which have not been done yet and discover the unexpected like we always do.

DR. HAMILTON: I did not find any problem with what Jim Clark has said today, or any reason to change our numbers as a result of the numbers he gave us, but they are not very much overlapped with ours.

MR. GALERNE: If the diver is a heavy smoker, you will have a tendency to have trouble sooner than with a guy that has a clean lung.

DR. LAMBERTSEN: I have no quarrel with the concept. It is a good one and I agree with you on the numbers.

From the SHAD II and SHAD III data those numbers may end up too low, because the people were satuated at 50 feet of air; 60 feet on SHAD II and 50 feet on SHAD III. So when they made their excursions had they come back to the surface like the kind of dives that other people are planning, they might have had more recovery overnight and the numbers based on SHAD might be more conservative than necessary.

DR. HAMILTON: SHAD III was over the top. SHAD II, the long one, is more relevant.

DR. LAMBERTSEN: But the point is they did not come back to surface. They came only to the 50 foot storage depth and, therefore, we may find there are some better figures with people that return to surface PO_2 every day.

DR. CLARK: We treat patients every day with typical doses at 2 hours at 2 atmospheres. Some patients get it only once and some twice, six days a week. We have not done extensive measurements in these people but they do not get symptoms of pulmonary toxicity. They get other things but they do not get symptoms of pulmonary toxicity.

UNIDENTIFIED PERSON: What are the other things?

DR. CLARK: Sometimes you see progressive myopia, normally reversible. Sometimes they get some tingling in fingertips. That is about it that we know of.

NURP/UNCW NITROX DIVING PROGRAM

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Mr. Dinsmore is Diving Officer at the University of North Carolina at Wilmington. He has led the development of a nitrox diving program in a university setting, including first convincing the university of its benefits, then developing gas mixing capability and on-board operational procedures, and finally training the dive crew and scientists.

ABSTRACT

Dinsmore DA. 1989. NURP/UNCW nitrox diving program. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

The NOAA Undersea Research Center at the University of North Carolina (NURC/UNCW) was established in 1980 to promote, facilitate, and conduct undersea research in the Southeastern United States. From its inception, NURC/UNCW was designed as a wet-diving program capable of putting the "scientist in the sea" using a mobile platform and state-of-the-art diving equipment and techniques. In 1986 the Center initiated a comprehensive research program utilizing manned submersibles, remotely operated vehicles, and mixed gas scuba systems. During implementation a surface supplied heliox method was tried but this gave way to scuba-oriented enriched air nitrox techniques. After trying the continuous mixing technique into a storage bank, mixing is now done directly into scuba cylinders. Several successful missions have been accomplished using enriched air nitrox.

INTRODUCTION

The NOAA Undersea Research Center at the University of North Carolina (NURC/UNCW) was established in 1980 to promote, facilitate, and conduct undersea research in the Southeastern United States. Serving as one of five regional undersea research programs funded by the National Oceanic and Atmospheric Administration (NOAA), NURC/UNCW was founded as a wet-diving program capable of putting scientists in the sea to conduct "hands on," in situ research. Utilizing the *R/V SEAHAWK* and a professional dive-support staff, scientists were able to conduct undersea research in a variety of locations using state-of-the-art scuba and surface-supplied air/mixed-gas diving equipment and techniques.

Although many successful missions were accomplished from 1980 through 1985, the Center's diving support vessel, (*R/V SEAHAWK*), proved to be ineffective in establishing and maintaining a three point moor required for surface-supplied diving operations. This fact, coupled with the extraordinary amount of equipment, training, and support personnel necessary to conduct deep diving operations, prompted the Center to curtail surface-supplied diving operations in December 1985.

In order to continue the tradition of providing safe and effective wet-diving research capabilities, NURC/UNCW implemented a comprehensive enriched air nitrox scuba program in 1986. Nitrox scuba was considered a viable alternative to surface-supplied diving for several reasons:

1. The use of nitrox would provide scientists extended bottom times.

2. With the exception of a few specialized pieces of equipment, standard scuba gear could be used.

3. The amount of classroom and practical training required was minimal.

4. The use of nitrox, with standard air decompression profiles, added an additional margin of safety.

IMPLEMENTATION

The establishment of NURC/UNCW's nitrox program involved adaptation of technology already in place from the earlier surface-supplied mixed-gas diving program. The implementation process involved three phases: Personnel training and certification, equipment modification, and procedures development.

The diving staff, already trained and experienced in mixed gas (HeO_2) diving operations, were easily cross-trained during a one-day seminar conducted by Dr. Morgan Wells from the NOAA Diving Office. During the seminar, Dr. Wells presented both theoretical and hands-on instruction in the use of nitrox including; historical development, theory of operation, physiological considerations, gas mixing and analysis, and NOAA Nitrox I. The information presented during the seminar, was used as the basis for NURC/UNCW's nitrox training course presented to scientists prior to participation in diving operations.

The modification of the Center's surface-supplied mixed gas diving system into an enriched air nitrox scuba system was the second phase of implementation. Three major issues had to be addressed:

1. Whether to use pre-mixed N_2-O_2 or mix the gas in house. Consultation with local compressed gas supply companies plus expected usage calculations quickly revealed the cost advantages of performing the mixing in house.

2. Whether to use pure gases or compressed air to mix nitrox. Although the cost of clean, oil-free nitrogen was fairly inexpensive, substantial savings could be realized using h.p. compressed air. Most importantly, the logistics involved with transporting and storing the nitrogen cylinders on vessels of opportunity was significantly greater than that of a small portable air compressor. Unfortunately, the Center's h.p. air compressors were not "oil-free", as required by NOAA, and could not be used for

mixing enriched air. Therefore, initial mixing procedures were performed using pure nitrogen in lieu of compressed air.

3. Whether to mix nitrox into bulk storage banks or into individual scuba cylinders. Upon recommendation from NOAA, the decision was made to mix into storage banks. A bank of twenty-four (24) h.p. "K" cylinders, originally used as an HeO_2 storage bank on the *R/V SEAHAWK* and still in "oxygen clean" condition, was used for nitrox storage.

The design and construction of the nitrox system was performed by staff personnel with guidance from the NOAA Diving Office. Parts and equipment used to build the system, with the exception of the "oil-free" air compressor, were scavenged from the *R/V SEAHAWK's* mixed gas (HeO2) system.

The development of operating procedures was the third phase of implementation and involved re-writing the Center's Diving Operations and Procedures Manual. Based on the NOAA Diving Manual and NOAA Directive 64-23, the NURC/UNCW manual specifically addresses those standards and procedures peculiar to the Center which are not covered in either reference. The manual serves as the guiding document for all diving operations conducted under the auspices of NURC/UNCW and includes the following categories:

Diving Standards

- Maximum Depth and Bottom Time
- Maximum Sea Conditions
- Personnel Requirements
- Equipment Requirements
- Hours of Operation
- Training Requirements
- Medical Requirements
- Diver Certification Requirements
- Record Keeping Requirements

Operating Procedures

- Pre and Post Diving Procedures
- Decompression Diving
- Line-Tended Scuba
- Mixed Gas (Nitrox) Diving
- Night Diving
- Recompression Chamber Operations
- Diver-Support Boat

Diving Accident Management

- Protocol
- Medical Consultation
- Notification of Authorities
- Post Treatment Requirements

The Operations Manual was forwarded to NOAA's Diving Office and the Office of Undersea Research for review and was approved in June 1986. One month later, the Center conducted its first nitrox diving mission with scientists from the South Carolina Wildlife and Marine Resources Department off the coast of South Carolina. Using NOAA Nitrox I, a total of 68 scuba dives were performed over a period of 4 days at depths ranging from 18 to 34 msw (60 - 110 fsw) with a total bottom time of 24 hours 26 minutes.

At the conclusion of the 1986 operating season, the *R/V SEAHAWK* was removed from service due to the vessel's aforementioned diving limitations. Simultaneously, during this period, a re-evaluation of the marine research needs of the southeast was conducted to help identify and determine future directions of NURC/UNCW. As a result of the study, recommendations from the Center's advisory board, (SECURE), and NOAA's Office of Undersea Research, the decision was made to maintain the Center's wet-diving capability using nitrox scuba, and to expand capabilities to include manned submersibles and remotely operated vehicles on a lease basis.

1987 OPERATIONS

Without the *R/V SEAHAWK* the Center had to develop a new nitrox diving system that was modular in design, highly portable, and capable of being operated on various vessels of opportunity. The system that was developed consisted of the following:

- air compressor; h.p. Rix "oil-free", electric-driven
- gas storage bank; h.p. compressed air and chamber support
- oxygen storage system
- mixing/charging station
- storage/workshop; portable 8' X 10'
- recompression chamber; double lock, 42" diameter (NOAA)
- air compressor; l.p. Quincy 5120, diesel-driven
- oxygen transfer pump, Haskel, air-driven

The system supported nitrox missions in 1987 in the Gulf of Maine and off the coast of South Carolina utilizing the *M/V SEAWARD EXPLORER*, a 105' offshore supply-type vessel leased from Seaward Services in Miami, Florida. A total of 212 nitrox scuba dives were performed over a period of 15 operational days at depths ranging from 25 to 40 msw (80 - 125 fsw) with a total bottom time of 40 hours 44 minutes.

During these two missions procedures and techniques were modified that greatly enhanced and improved the enriched air nitrox operations. One modification involved changing the mixing techniques used at sea. Initially, N_2/O_2 was mixed by cascading or pumping, via a Haskel transfer pump, pure oxygen into a bulk storage bank, and then topping the cylinders off with "oil-free" compressed air. The gas would then be cascaded or pumped into individual scuba cylinders. The technique, used several times during the first mission, proved to be inefficient, time-consuming, and inaccurate. Additionally, the volume of gas we were able to mix and store in a given day was insufficient to meet diving requirements. Therefore, we then began to mix nitrox directly into individual scuba cylinders using the system diagrammed below.

The technique used to mix N_2/O_2 into scuba cylinders was identical to that used with the bulk storage cylinders; however, the procedure could be performed more quickly and accurately due to the small quantity being mixed. This was an advantage when the mixture required adjustment in the oxygen content since little or no gas was wasted during the process.

To adjust for nitrox mixtures containing too much oxygen, the pressure in the cylinder was bled to a specific point, and then re-filled with compressed air. In general, the amount of pressure bled was determined by the following rule-of-thumb:

For every 0.5% (one-half of one percent) of oxygen over the desired amount, reduce the pressure in the cylinder by 100 psi and refill with air.

If the oxygen content was too low, the cylinder was normally drained completely and the mixing process repeated.

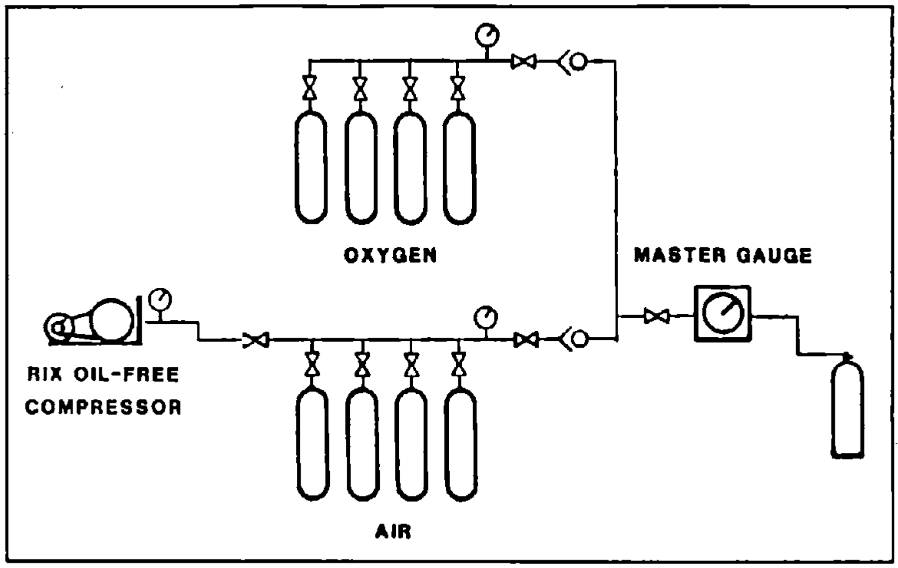

Figure 1 NURP/UNCW nitrox mixing system.

A table listing the specific volumes of oxygen and compressed air, (in psi) required to achieve a 32% oxygen mixture was developed to facilitate mixing of partially filled cylinders. Table 1 was calculated for a NOAA Nitrox I mixture using 80 ft^3 scuba cylinders @ 3000 psi.

1988 AND BEYOND

To date, NURC/UNCW has conducted 282 nitrox dives during three missions at depths ranging from 18 - 40 msw (60 - 125 fsw) for a total bottom time of 65 hours 10 minutes. All dives were performed using open-circuit scuba equipment with NOAA Nitrox I (32% oxygen, 68% nitrogen) breathing mixtures and were within USN no-decompression and normal oxygen partial pressure limits. No incidence of bends or other diving maladies were recorded during the dives despite many repetitive dives performed in cold (4C) water.

It is anticipated that four nitrox scuba research missions will be conducted in 1988. One enhancement expected for these missions includes the use of wireless communications integrated into EXO-26 full-face masks. This system will be capable of interfacing with a self-contained

Table 1. Specific volumes of oxygen, in psi, required to mix partially filled cylinders with NOAA Nitrox I

Tank PSI	Oxygen PSI	Combination
0	420	420
100	400	500
200	390	590
300	380	680
400	360	760
500	350	850
600	330	930
700	320	1020
800	310	1110
900	290	1190
1000	280	1280
1100	260	1360
1200	250	1450
1300	240	1540

underwater video camera, and will allow scientists the ability to communicate with topside personnel and record *in-situ* observations while in a free swimming mode. NURC/UNCW also plans to conduct a study on nitrox rebreathers, to determine their applicability to scientific data collection. The study will include open-sea test dives off the coast of North Carolina and will involve participants from the NOAA Diving Office and Harbor Branch Oceanographic Institution. Concurrently, NURC/UNCW will initiate a study to determine the validity of the equivalent air depth (EAD) concept with a wide range of nitrox mixtures as a means of increasing diver safety and efficiency.

Working closely with NOAA's Diving Office and the Office of Undersea Research, NURC/UNCW is in a unique position to play an important role in the development and testing of new and innovative tools and procedures to enhance undersea research capabilities. In the future, NURC/UNCW will continue to play a leading role in the use and development of nitrox in support of scientific investigations.

Discussion following Mr. Dinsmore:

MR. RUTKOWSKI: You made a statement there that I would like clarification on, because this document we are putting together here for this Workshop is undoubtedly going to be a guide to many of the other people in the industry. Why do you require an oxygen tolerance test? Is that a NOAA requirement or is that your own personal thing?

MR. DINSMORE: As far as I know, it is not a NOAA requirement.

MR. RUTKOWSKI: Are we going to make it a statement of this Workshop that it is going to be a requirement?

MR. DINSMORE: At this point it has been determined to be a requirement of our program, the NURC program at UNCW. There is a question about its validity, but we feel it is an appropriate thing to do for our program.

DR. HAMILTON: It does not do much to show whether you are going to be an oxygen casualty or not, but it is very helpful to show whether you are emotionally suited to diving and being treated.

MR. RUTKOWSKI: Please understand that many organizations will review this Workshop. Is an oxygen tolerance test a requirement to do nitrox diving or not, yes or no. I do not care about NURC. Is it a NOAA requirement?

MR. DINSMORE: No, it is not a NOAA requirement.

MR. HULBERT: We use it as part of our training program. It is important to us because we bring in scientists from all over the place and as such it is exactly what Dr. Hamilton way saying. It is a way of telling whether people are going to get uneasy under pressure when you confine them.

UNIDENTIFIED PERSON: You can do that with air.

MR. DINSMORE: You can do that with air but we feel we are accomplishing something with an oxygen test.

MR. RUTKOWSKI: Whenever we have a chamber on board and we have scientists come on board, sure, in order to do exactly what he said, to relieve a lot of apprehension, to make them familiar with the face mask and the chamber and so on, we could camouflage under the auspices of them doing a tolerance test. But I do not see the requirement, and I hope that is what this Workshop will conclude.

MR. DINSMORE: We are all authorized to do decompression diving. Just like the Navy is doing, students going through naval diving school will still go through an oxygen tolerance test, correct?

CAPT HARVEY: Yes.

MR. RUTKOWSKI: What about the work that was done by Chris Lambertsen on the validity of oxygen tolerance testing, which was done for NOAA?

DR. LAMBERTSEN: I do not remember exactly what you are talking about but I think you ought to again separate whether some agency happens to have a policy from whether it is sensible or not. It sounds as though the Navy has a policy which is not sensible, and NOAA at this time has a policy which is sensible.

DR. CROSSON: I am certainly in full support of not using PO_2 tolerance test. I do not, however, think it is the responsibility of this Workshop to come up with a decision one way or the other on that matter.

I think the purpose of this Workshop was to share information. If we have to come up with a set of guidelines, if you guys want us to book you for another couple of weeks, we can do that. But we are not doing that in a lot of areas, not just PO_2 tolerance. I really wish we could come up with guidelines, but that is not really the purpose. As far as recommendations, I think they are coming out.

MR. RUTKOWSKI: Dave Dinsmore made a statement, that statement is going to be reviewed by everybody that I may train, no matter if it is military, commercial, or whom, and I will have to provide them an oxygen tolerance test now because NOAA says it is a requirement, but NOAA does not say it is a requirement. I want NOAA to say point blank that it is not a requirement for their program.

MR. HULBERT: We operate under a two tiered set of regulations. Our grant comes from NOAA; therefore, we have to go under NOAA regulations. We are also a university; therefore, we have to dive under university regulations as well, and our manual incorporates both of those.

MR. RUTKOWSKI: But you are using the O_2 test as a training tool. As a test it does not approximate 1.6, because 1.6 is as much as you are pushing on this concept. Sports divers push it every day, and they do not have a problem and they do not go down and get a tolerance test.

DR. CLARK: The whole purpose of an oxygen tolerance test was reviewed very thoroughly by Butler and Thalmann. They surveyed over a period of 10 years with respect to what an oxygen tolerance test was and they looked at a total of almost 1350 oxygen tolerance tests. There was just under a 2% incident of positive tests and 10 of those were convulsions. So 10 Navy trainees or potential trainees convulsed in 30 minutes at 2.8 atm and that is totally different from what we have seen in subjects, normal resting subjects under virtually the same conditions. It makes you wonder under what circumstances those tests are done.

CAPT HARVEY: One of the Navy's rationales for doing the oxygen test is that if we find a person who is sensitive--if that is what the test is testing for--we would prefer not to find it out when we are treating a guy after a decompression sickness hit. We have taken the position that one of our goals is to screen these people out so that while they will not be exposed during the diving, they may be for a treatment. So we have chosen to keep it.

DR. DAUGHERTY: Given the talk that has been heard here about its variability and the widespread knowledge on how people's lungs react to oxygen, what is the harm in doing it as a way of screening out 2%, one person in fifty? What is the harm in it?

MR. RUTKOWSKI: The harm is making it a requirement. If you make it a requirement, you just about eliminate the nitrox concept for most of the people in this room.

DR. DAUGHERTY: You are talking about 2.8 atmospheres in a chamber.

MR. RUTKOWSKI: Sure, I have a chamber in Key Largo, but how many people here have a chamber where they can to this testing.

DR. DAUGHERTY: He is talking about a program where a bunch of outsiders and strangers, many of them middle aged and not in outstanding condition, are coming in and he is talking about putting them at 2.8 atm and in effect is trying to filter out the small, small minority who will have a reaction.

MR. RUTKOWSKI: He is setting a public standard. This document is going to be a public document.

DR. DAUGHERTY: I do not agree with that. All he is saying is what he does up in Wilmington.

MR. RUTKOWSKI: I want him to clarify it that this group does not consider it to be a mandatory or a necessary part.

DR. CROSSON: I think it suffices to say that we want it on the record; it is an individual program decision. The programs may not decide to, and apparently the majority of the programs would not, but let it go on record that the majority of them do not. But the case is, if you choose to do so, that is certainly your decision.

DR. LAMBERTSEN: I want to clarify what I meant by saying that the doing of the tolerance test as a requirement by the Navy was not sensible. This has been dealt with over and over again by the Navy and others of us over many years, 20 or more, okay? What seems to be the case is that the manner of doing the test, the equipment that is used to do the test, can be a prominent factor in whether or not someone gets convulsions as opposed to showing tolerance of that individual to oxygen. That is one thing.

The second thing is that Gordon talked about the lung. The lung is not involved in that oxygen test.

DR. DAUGHERTY: No, sir, I said one of the themes here was the variation among individuals, with lungs and other tissues.

DR. LAMBERTSEN: So pulmonary variation has nothing to do with it. It is a CNS test, not a pulmonary test.

DR. DAUGHERTY: I did not say it was. I said that variation among people was one of the things that was brought out here.

DR. LAMBERTSEN: The main point is that the tolerance of individuals is probably much greater than is the expression of that tolerance in an oxygen tolerance test, simply because of the kinds of apparatus that are used, with rebreathing and things of that sort. That seemed to have been the earlier opinion, but it stuck as a requirement. It then got its purpose changed, as Dr. Harvey, said from a requirement for diving to one in which that is put aside.

Is that so, Claude? Now the requirement bears no requirement on the original requirement. As long as those things are known, then you can think about it.

DR. CROSSON: Given the program you have, Dave, how does it work out in terms of having a mobile nitrox program?

MR. DINSMORE: Due to the fact that we are located right in Wilmington, which is a seaport, it has not been difficult at all to transport these major components down to the dock at the port, where the vessel that we lease comes in. We have a good rapport with the state port authority, and they load them right on the boat. It has not hindered us at all, really.

MR. STANTON: I noticed from your slides and whatnot that you have had some experience out in the field with this now. Do you have a cost-benefit ratio as compared to air from a practical standpoint, not from a theoretical one?

MR. DINSMORE: No, I sure do not. I know it is buying us extra time.

MR. STANTON: At what cost?

MR. HULBERT: Oxygen is cheap.

MR. RUTKOWSKI: Based on $18.00 a bottle for oxygen, it comes out to about 70¢ for an 80 cubic foot tank.

MR. DINSMORE: And we are getting oxygen for $5.00 a tank.

MR. STANTON: That is not cost.

MR. GALERNE: If I can make only one comment which I hope you do not take as a criticism. I see one thing wrong on your installation. Your bottle is horizontal. In case of fire, the bottle is horizontal, this is against the insurance standpoint, because if you have a fire, the pressure increases and the valve goes out and it kills everybody in front.

MR. DINSMORE: That is something we are going to change this year. We are putting the O_2 in a bottle rack this year.

MR. GALERNE: Another advantage is, if your mixture is not mixed you heat the bottom of the bottle and you do not have to move them.

MR. DINSMORE: When we initially mixed on the *SEAHAWK* using pure gas, that is exactly what we did. We put a space heater right up beside the bottle, and it worked.

DR. WELLS: Dave, how many teams of divers within a one day period could you comfortably use going in and out of that compressor, filling the bottles and so forth? Were you running that thing nonstop 24 hours a day?

MR. DINSMORE: The crew in the main worked us to death. We were doing 10 sets a day, 5 in the morning and 5 in the afternoon, double tanks, and we were keeping up. Our staff was staying up until midnight, getting gasses mixed and ready for the next day. That is turning it around quickly, mixing while the next team is in the water, mixing for the next one.

MR. NORRIS: Do you know how much you extended your actual diver time to do work by going to nitrox versus doing the same mixture on air?

MR. DINSMORE: No.

MR. NORRIS: Have you got an estimate?

MR. DINSMORE: It has to be 25% more. What is critical, and I hope everybody understands this, when a scientist puts down an experiment and it is down and it is collecting data, he has to get back to get that if he is to be successful. Two or three minutes more can make the difference in whether or not he can get the data. A little bit more time on that second dive can make all the difference in the world.

DR. VANN: Pertaining to the question of mixing, has anybody looked at putting a distribution system down in the tank so that rather than having a single point of injection, you inject throughout the length of the tank and therefore get more effective mixing?

DR. HAMILTON: Yes.

MR. DINSMORE: We had tremendous luck putting the oxygen in and topping it off with the air. It seemed to mix almost instantaneously. So we had real good luck mixing with that small of quantity versus a "K" cylinder or a bank of "K" cylinders.

DR. WELLS: I will tell one little sea story. During our nitrox course, we got a mix that was too rich in one of the scuba bottles on that system that I showed you. In this case the mixture was too rich. So I just hooked it up and blew some air into it. While it was standing vertically we hooked it up to the analyzer, opened it up, and almost pure air was coming out of that cylinder. So while the analyzer was running I flipped the bottle upside down; you can in your mind just visualize this density mixture. Suddenly the rich mix started coming out again because it was a little heavier than the air. Even in a scuba bottle you can have layering if you do not move these things. It is a very dramatic thing to turn it upside down and see the rich mix start coming out.

THE PHYSIOLOGY OF NITROX DIVING

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Dr. Vann works at the F.G. Hall Laboratory at Duke University. His experience in both modelling and evaluating decompression tables blends well with his knowledge of diving physiology to produce an overview of the role of physiological principles and experience as they relate to nitrox diving.

ABSTRACT

Vann RD. 1989. The physiology of nitrox diving. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

Both efficiency and reliability of decompression can be improved by judicious use of oxygen. One aspect of this is the EAD, or equivalent air depth, a principle which states that only the nitrogen partial pressure need be considered in non-air dives with nitrogen-oxygen mixtures. Limited support for this concept comes from several studies, and none give cause for regarding it as invalid. The choice of decompression tables for EAD diving calls the reliability of available tables into question, but tables reliable for air diving should be good for use with the EAD. Decompression by computer offers an attractive option, but to date none is available for EAD diving.

INTRODUCTION

The most efficient means of improving decompression is by the use of oxygen. Diluting the nitrogen in air by adding oxygen provides a decompression advantage since oxygen metabolized in tissue does not contribute to the bubbles that cause decompression sickness. This is the basis of the Equivalent Air Depth (EAD) theory which assumes that oxygen is totally metabolized and only nitrogen is important in decompression calculations.

THE FATE OF OXYGEN

The EAD is the depth of an imaginary air dive that would have the same nitrogen partial pressure as an actual dive on oxygen-enriched air. The EAD is given by

$$EAD = \frac{(1-F_IO_2)(D + 33\ fsw)}{0.79} - 33\ fsw$$

where D is the actual depth and F_IO_2 is the inspired oxygen fraction. The EAD theory allows existing decompression tables to be used with oxygen-enriched air. If the actual depth is 130 fsw and the F_IO_2 is 0.32, for example, the EAD will be 107 fsw and air decompression schedules for 110 fsw should be used.

How valid is the assumption that oxygen does not contribute to decompression sickness? Metabolism converts oxygen, a relatively insoluble gas, into carbon dioxide which is some 21 times more soluble. The effect of exchanging oxygen for carbon dioxide on dissolved gas tension is illustrated in Figure 1. The x-axis is dissolved gas tension in torr, and the y-axis is dissolved gas content in ml gas per 1000 ml blood. The steeper line shows the relationship between CO_2 tension and content. The slope of this line is the CO_2 solubility. The other line represents the same relationship for oxygen. Its gradual slope reflects the lower oxygen solubility.

Suppose, as indicated by Point 1 in Fig. 1, the oxygen tension were 100 torr. This corresponds to an oxygen content of 3 ml of oxygen per 1000 ml of blood (Point 2). If each O_2 molecule were exchanged for a CO_2 molecule (Point 3), the dissolved gas volume would be unchanged, but the tension would fall to 4.7 torr (Point 4). This is because CO_2 is more soluble than oxygen.

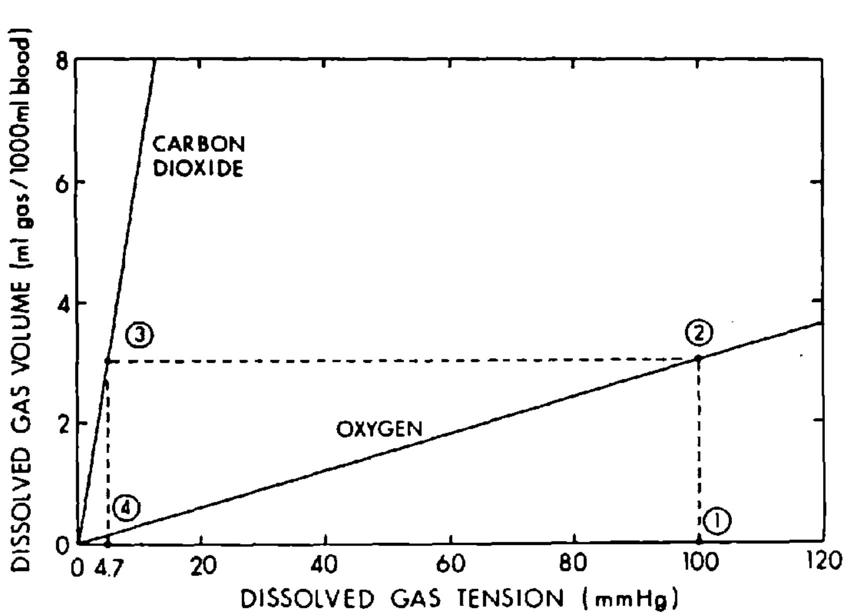

Figure 1. The effects of exchanging oxygen for carbon dioxide on dissolved gas tension. When oxygen is converted into carbon dioxide, the gas tension falls from 100 to 4.7 torr. but the dissolved gas volume remains unchanged because carbon dioxide is more soluble than oxygen (Vann, 1988).

Most of the oxygen carried by blood, however, is chemically bound to hemoglobin, and under normal conditions, only a small fraction is dissolved. Figure 2 shows the total oxygen content of blood in ml oxygen per 100 ml blood, a unit known as volume %, as a function of the oxygen tension. Point A1 is the arterial blood of a diver breathing air at sea level. Hemoglobin is nearly saturated with oxygen under these conditions. As the arterial blood passes through tissue, 5 vol% of oxygen are removed and converted to CO_2. This causes the venous oxygen tension (indicated by Point V1) to fall to 46 torr.

Now consider a diver breathing air at 3.5 ATA. His alveolar oxygen partial pressure is 504 torr, but his arterial tension is only about 450 torr as a result of ventilation-perfusion inequalities in his lungs. This is shown as Point A2 in Fig. 2. When 5 vol% of oxygen are extracted by tissue, the venous tension (point V2) falls to 53 torr.

Now the diver switches to 100% oxygen at 3.5 ATA and his alveolar partial pressure rises to 2,570 torr. Ventilation-perfusion inequalities reduce the oxygen tension in his arterial blood to around 2,000 torr (Lambertsen, et al, 1953). This is shown as Point A3 in Fig. 2. Here, however, the venous tension (Point V3) rises to 380 torr, far above the previous venous values. This unusually high venous tension occurs because the metabolic requirements of tissue are met entirely by dissolved oxygen. Venous hemoglobin remains saturated and on the flat rather than on the steep part of the oxygen content curve.

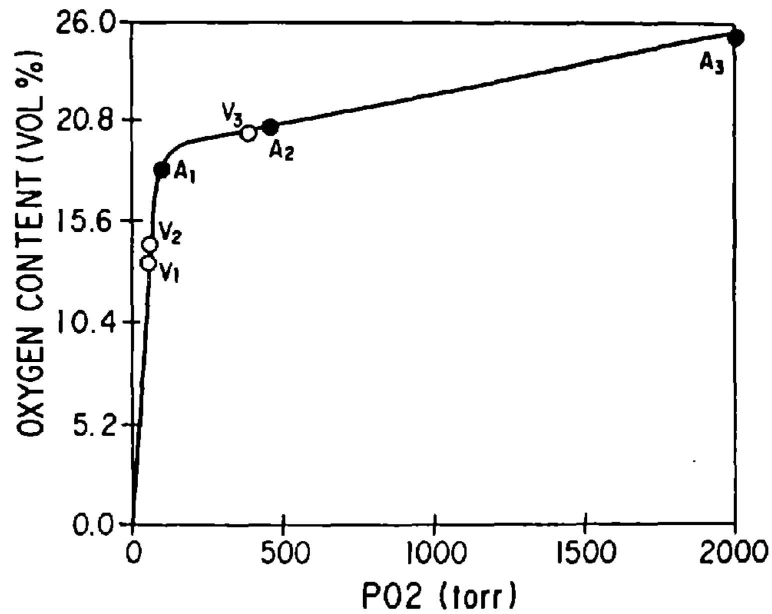

Figure 2. The total blood oxygen content in vol % (ml 02 /100 ml blood) as a function of blood oxygen tension. Total content is the physically dissolved oxygen plus the oxygen chemically bound to hemoglobin. The points marked A1, A2, A3 and V1, V2, V3 are approximate arterial and venous oxygen tensions during air breathing at sea level, during air breathing at 3.5 ATM, and during oxygen breathing at 3.5 ATM. The oxygen extraction from blood is taken as 5 vol %.

Tissue oxygen extraction is a function of both metabolism and blood flow. The oxygen extraction was 5 vol% in Fig. 2, but this is not true throughout the body. Table 1 lists a range of oxygen extractions for various tissues and organs and indicates that the extraction can be as high as 10 and low as 1.3 vol%.

Table 1. Oxygen extraction (ml/100 ml blood) in various tissues and organs (Folkow and Neil, 1971).

Heart	10
Brain	6
G.I. tract	6
Resting muscle	5
Kidney	1.3
Remainder	5

The effect of oxygen extraction on venous tension is shown in Fig. 3 as a function of arterial tension. The lowest curve, which represents an extraction of 6 vol%, indicates that the venous tension rises gradually at arterial tensions of up to 2,000 torr. At extractions of 5 and lower, however, the venous tension increases precipitously. At the lowest extractions, the venous oxygen tension can contribute more than an atmosphere to the dissolved gas tension. When added to nitrogen already dissolved in tissue, it is easy to imagine that oxygen might potentiate bubble formation and lead to a condition which Donald (1955) called "oxygen

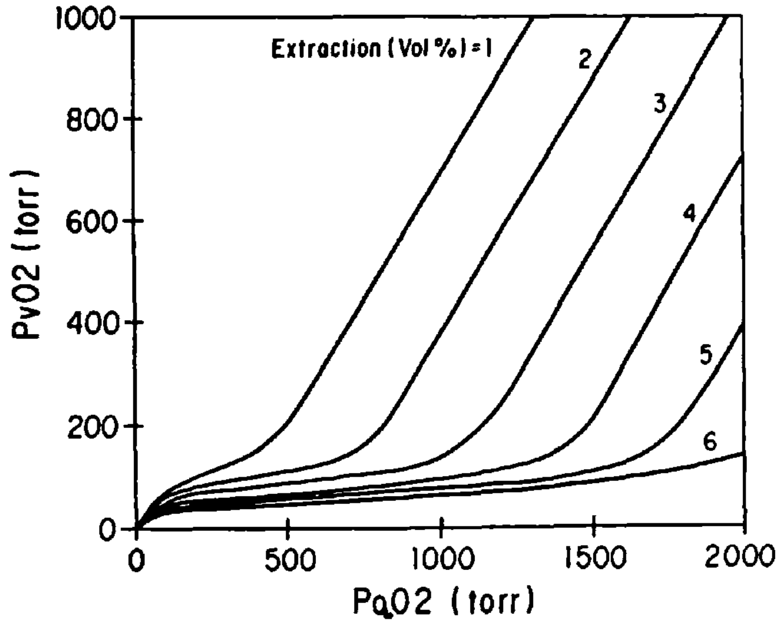

Figure 3. The effect of oxygen extraction on venous oxygen tension (P_vO_2) as a function of arterial oxygen tension (P_aO_2). At higher oxygen extractions, P_vO_2 remains relatively constant as P_aO_2 rises. In tissues with lower extraction, P_vO_2 rises steeply at high P_aO_2. This increase begins sooner at lower extractions. Since elevated $P_vO_2$contributes to bubble formation, the error in the EAD theory becomes greater as P_vO_2 rises.

bends." The EAD assumption that oxygen is totally metabolized, while only slightly in error at low inspired partial pressure, fails badly at high partial pressure.

"OXYGEN BENDS"

What insight concerning oxygen bends does experiment provide? Berghage and McCracken (1979a,b) determined the pressure reduction which produced a 50% DCS incidence (or ED50) in rats exposed on helium-oxygen to various pressures, times, and P_IO_2's. If there were no error in the EAD theory, an increase in P_IO_2 would lead to an equal increase in pressure reduction, or

$$[(P_IO_2)2 - (P_IO_2)1] = [\text{ delta P2 - delta P1}]$$

If these quantities are not equal, however, their difference represents an error in the EAD theory. Dividing this difference by the larger P_IO_2 defines that part of the oxygen which contributes to decompression sickness. Expressed as a percentage, this quantity will be called the % EAD Error.

$$\%\text{ EAD Error} = 100\% \times \frac{[(P_IO_2)2 - (P_IO_2)1] - [\text{delta P2 - delta P1}]}{(P_IO_2)2}$$

Figure 4 presents the % EAD Error calculated from data of Berghage and McCracken (1979a) as a function of P_IO_2. All EAD Errors are defined relative to the lowest P_IO_2 and are widely scattered over both positive and negative values. The heavy line, which shows the mean error, suggests that the EAD theory holds reasonably well at low P_IO_2's but becomes progressively worse at higher P_IO_2's.

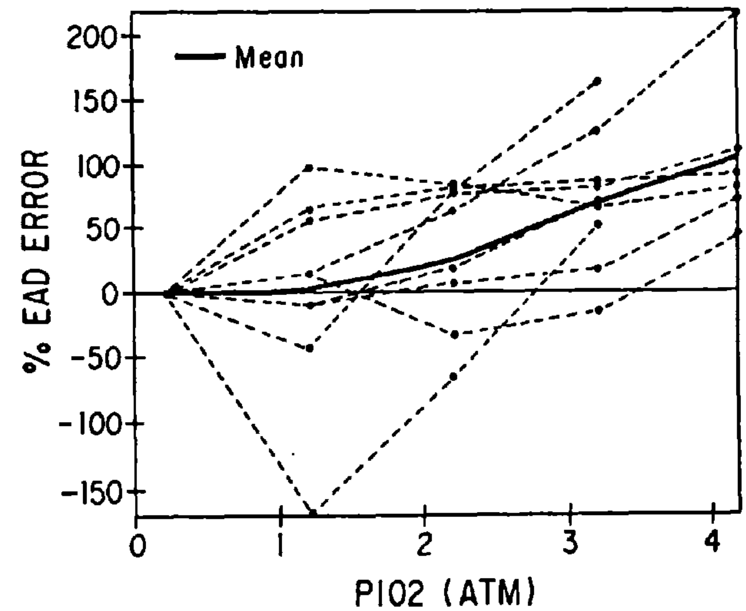

Figure 4. The % EAD Error as a function of P_IO_2 for the data of Berghage and McCracken (1979a). Saturation pressures were 10, 25, and 40 ATA with exposure times of 30, 60, and 120 min.

Figure 5 shows data from Berghage and McCracken (1979b) and from Rashbass and Eaton (1957). There is less scatter in the second Berghage study although fewer P_IO_2's were tested. The heavy line, indicating the mean values, suggests that over half the oxygen at 2.2 and 3.2 atm contributes to decompression sickness.

The lowest line in Fig. 5 is from Rashbass and Eaton (1957) who found the ED50 of rats compressed for 20 min to various depths and P_IO_2's prior to decompression to sea level. With this experimental design, the % EAD Error is given by the increase in P_IO_2 less the increase in ED50 pressure.

$$\% \text{ EAD Error} = 100 \times \frac{[(P_IO_2)2 - (P_IO_2)1] - [PB2 - PB1]}{(P_IO_2)2}$$

Rashbass and Eaton's data indicate that the EAD theory is valid between 0.2 and 2 atm and in error by 20% at 3.5 atm.

Lillo (1988) exposed rats to 141 fsw of nitrogen and 1, 2, or 3 atm of oxygen for various bottom times. Figure 6 shows how the percent non-fatal DCS and percent fatal plus non-fatal DCS increased with P_IO_2 after saturation exposures. The 50% increase for both end-points between 1 and 3 atm of oxygen indicates a substantial EAD error.

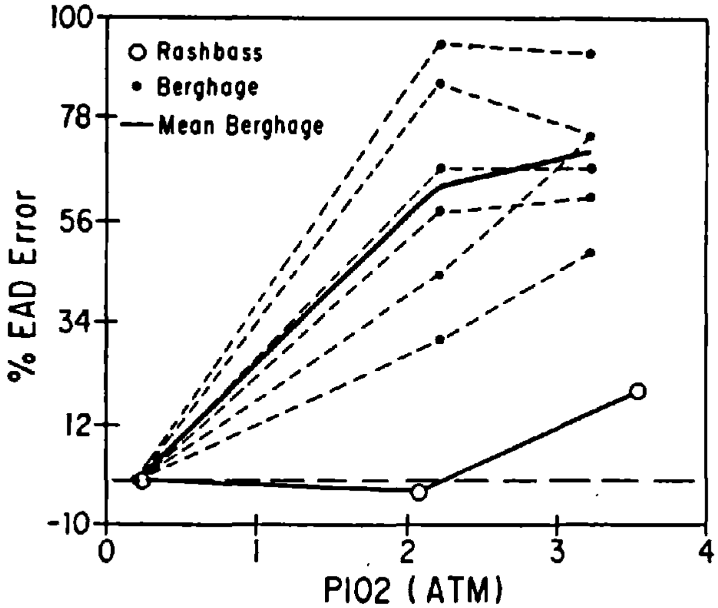

Figure 5. The % EAD Error as a function of P_IO_2 for data from Berghage and McCracken (1979b) and from Rashbass and Eaton (1957). Berghage and McCracken (1979b) used a saturation pressure of 15 ATA and exposure times of 1, 5, 10, 20, 40, and 80 min. The P_IO_2 after the pressure reduction was 0.5 ATM. Mean values are indicated by the heavy line. Rashbass and Eaton (1957) compressed rats from sea level to pressures ranging from 7 to 11 ATA for 20 min at various P_IO_2's in nitrox. Decompression back to sea level took 15 sec.

Donald (1955) was the first to address the question of oxygen in the EAD theory. He exposed 7 goats to a 60 min air dive at 50 fsw with a P_IO_2 of 0.53 atm. None of these animals developed DCS. When the P_IO_2 was raised to 3.53 atm with the same nitrogen content, however, 6 of 7 animals developed serious but transient symptoms. Five recovered spontaneously at sea level and one needed recompression. These results, shown in Fig. 7, indicate that oxygen is not an innocuous gas at 3.53 atm. Nevertheless, the spontaneous recovery from serious symptoms suggests that oxygen bends are probably less harmful than nitrogen bends. Presumably, the excess oxygen in bubbles is rapidly absorbed upon

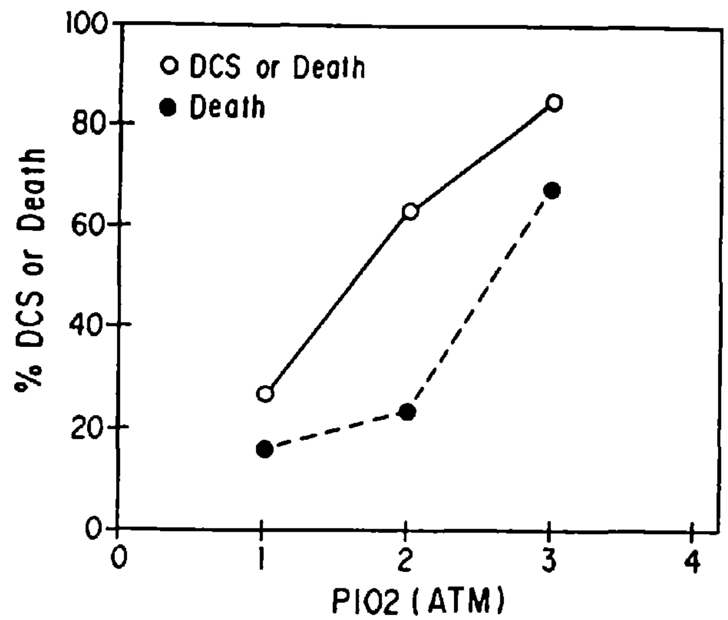

Figure 6. Fatal and non-fatal DCS for rats compressed to 141 fsw of nitrogen with 1, 2, or 3 ATM of oxygen. From Lillo (1988) based upon his analysis at saturation exposure.

decompression to sea level and return to normal P_IO_2.

Eaton and Hempleman (1973) decompressed goats from elevated pressure to sea level to determine the bends threshold pressure. They tested various P_IO_2's during 18, 50, and 180 min nitrox dives and during 120 min heliox dives. Figure 8 shows the % EAD Error as a function of P_IO_2. The errors varied from 10 to 20% for nitrox but were negative for heliox.

Two studies have investigated the EAD theory in humans. Logan (1961) tested 15, 30, 60, and 180 min nitrox dives at high and low P_IO_2's but the same nitrogen partial pressure. The DCS incidences from these tests are shown in Fig. 9 as a function of P_IO_2. Three studies were inconclusive because DCS did not occur on any dive. During 2 studies, one incident occurred in 5 trials at the lower P_IO_2 and 2 incidents occurred in 5 trials at the higher P_IO_2. These results are reflected by the increase in incidence from 20 to 40%.

Weathersby et al (1986) tested 30, 60, and 240 min nitrox dives at various depths and P_IO_2's. The mean DCS incidences at high and low P_IO_2 are shown in Fig. 9 for each bottom time. Each point represents the average of 76 to 82 dives. The incidence increased slightly at the higher P_IO_2 in one study and decreased in two studies. This could indicate either higher or lower risk at elevated P_IO_2, but neither conclusion was supported statistically. A lower risk might be explained by decreased tissue perfusion and nitrogen uptake due to oxygen-induced vasoconstriction.

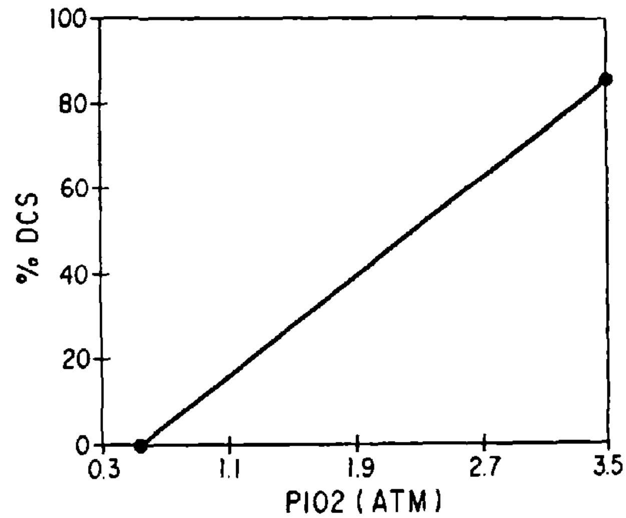

Figure 7. The DCS incidence of 7 goats with 2 ATM of nitrogen and 0.53 or 3.53 ATM of oxygen (Donald, 1955).

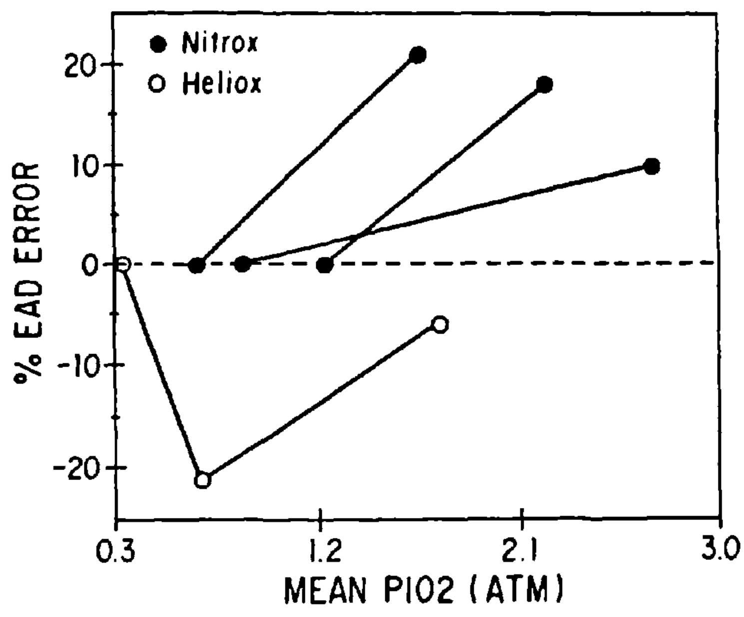

Figure 8. The % EAD Error as a function of P_IO_2 for goats decompressed to sea level after exposure to various pressures for 18, 50, and 180 min nitrox dives and 120 min heliox dives (Eaton and Hempleman, 1973).

Species differences, differences in experimental design, rapid decompression rates, and severe symptom end points may render some of the previous studies inapplicable to humans. Qualitatively, these studies show that EAD errors are smallest at low P_IO_2 and larger at high P_IO_2. This is consistent with the nature of oxygen transport in blood. Of the human studies, Logan concluded (on the basis of too few experiments) that oxygen partial pressures between about 1.2 and 1.6 atm make a small, but not statistically significant, contribution to decompression risk and that this risk does not warrant abandoning the EAD theory. The Weathersby data does nothing to contest this conclusion, at least up to oxygen partial pressures of 1.3 atm.

NITROX DIVING AND DECOMPRESSION

How effective is nitrox diving at reducing decompression risk and time? We studied this question during 60 min dives to 100 and 150 fsw (Vann, 1982). A goal of at least 20 safe trials was set for each decompression schedule tested although as many as 30 trials were conducted. While this is more testing than is frequently used, the binomial probability theorem still indicates less statistical confidence than is desirable. With 20 safe tests, for example, the confidence level that a schedule will not produce more than a 5% DCS incidence is 64%. With 30 safe tests, the confidence level is 79%. To achieve a 95% confidence level, 60 safe tests are required. A schedule which caused decompression sickness was usually not tested again because more trials are needed to achieve the same confidence level than for a schedule tested without incident.

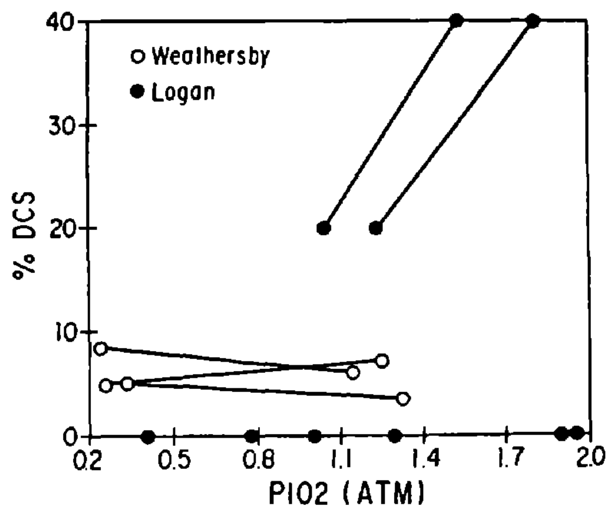

Figure 9. The DCS incidence as a function of P_IO_2 for humans from studies of Logan (1961) and Weathersby, et al. (1986).

The dives took place in a wet pot with the divers exercising at depth at an oxygen consumption of 1 lpm and resting during decompression. The water temperature was 20-25C, and full wet suits were used. The divers were Navy SEAL's, and the breathing apparatus was the Navy's Mk 15 UBA. The Mk 15 is a closed-circuit, mixed-gas scuba which controls the P_IO_2 independent of depth to a set point of 0.7 atm. Modifications to one Mk 15 made the set point adjustable and allowed the diver's oxygen consumption to be measured in real time as an index of workload.

The use of elevated oxygen partial pressure is limited by CNS oxygen toxicity. During one 100 fsw dive with a 1.6 atm set point, an oxygen convulsion occurred after 40 min of moderate to heavy work. The diver later reported, and bench tests confirmed, that the breathing apparatus had excessive respiratory resistance. This can cause CO_2 retention leading to an early onset of oxygen toxicity (Lambertsen, 1974; Piantadosi et al, 1979). Accordingly, the apparatus was modified to reduce resistance, and the divers were instructed not to "overbreathe" the equipment or work to the point of dyspnea. The oxygen set point was lowered to 1.4 atm in subsequent trials, and no further symptoms of oxygen toxicity occurred during exposures of up to 160 min.

Table 2 shows the results of decompression trials with oxygen set points of 0.7 and 1.4 atm. After the 100 fsw dive at 0.7 atm, one DCS incident occurred in 11 trials of an 80 min schedule. A 90 min schedule was tested safely 29 times. With the 1.4 atm set-point, a 20 min schedule was tested safely in 27 trials. The 150 fsw dive was attempted unsuccessfully at 0.7 atm in one trial of a 195 min long schedule, but a 100 min schedule was tested safely in 20 trials at 1.4 atm. There was one DCS incident in 11 trials of a 90 min schedule. Very few intravascular bubbles were detected by precordial Doppler after the safe schedules.

Table 2. The effect of oxygen partial pressure on decompression during 60 min dives at 100 and 150 fsw (Vann, 1982). The divers did light work (1 lpm oxygen consumption) at depth and rested during decompression.

Depth (fsw)	PIO2 (ATM)	Decomp Time	DCS/ Dives	Mean Doppler	EAD (fsw)	USN Decom time (min)
100	0.7	80 min	1/5	1.0	106	56
	0.7	90	0/29	0.4		
	1.4	20	0/27	0.1	77	20
150	0.7	195	1/1	4.0	169	152
	1.4	90	1/11	0.5		

The last decompression stop during the 1.4 atm schedules was placed at 20 rather than 10 fsw to take advantage of the larger oxygen window and accelerate nitrogen elimination (Vann, 1982). The 1.4 atm set-point could not be maintained at 20 fsw, however, without exhausting gas from the Mk 15 breathing loop into the water and depleting the oxygen supply. This problem was largely overcome by reducing the set-point at 20 fsw from 1.4 atm (87% oxygen) to 1.3 atm (81% oxygen). Placing the final stop at 20 fsw rather than at 10 fsw also allows better depth control during open water diving.

Table 2 shows the EAD's for the these dives and the corresponding Navy Standard Air Decompression times. At 100 fsw and 0.7 atm, the time for safe decompression was about twice that of the Navy tables. At 1.4 atm for both the 100 and 150 fsw dives, the decompression time was nearly the same as the Navy EAD time. These results suggest that the corresponding Navy schedules may be less than satisfactory when used with an air breathing medium.

DECOMPRESSION TABLES

The most common nitrox diving technique employs a mixture with a fixed oxygen percentage rather than a fixed partial pressure. The U.S. and Royal Navies had standard nitrox mixes of 32.5, 40, and 60% oxygen for use with semi-closed circuit scuba. The U.S. Navy provided a list of Equivalent Air Depths so that these mixtures could be used with the Standard Air Decompression Tables. They also provided and taught the equation for calculating the EAD at any oxygen percentage (U.S. Navy Diving Manual, 1963).

The new French national decompression tables developed by COMEX provide EAD lists for mixtures ranging from 25 to 50% oxygen in 5% increments (Imbert and Bontoux, 1987). These mixes can be used with any decompression table, including in-water oxygen decompression and surface decompression. Other than the additional training and care needed to split, mix, and analyze gas, and the operational problem of depth control, there appears to be no reason against and sufficient precedent for using the EAD theory with any gas mix at oxygen partial pressures of up to at least 1.3 atm and possibly as high as 2 atm.

A much more difficult problem, however, is the choice of a decompression table to use with the EAD theory. The first axiom pertaining to this choice is that all decompression tables which allow useful work are associated with a finite risk of decompression sickness. What constitutes acceptable risk has yet to be agreed upon, but somewhere between 0.1 and 1% may not be an unreasonable number. Note that the term "acceptable risk" applies to dives at the full extent of permitted depth and bottom time. As most dives do not approach these limits, bends incidences in the literature such as 0.03% or 0.01% (Bove, 1987) do not accurately measure table safety.

A second axiom in selecting a decompression table is that there is little data on which to base a risk assessment and much of this data is concentrated around no-stop and single exposure dives. Existing evidence concerning the widely used Navy tables, for example, suggests the no-stop limits and short decompression dives are reasonably safe for single exposures, but dives requiring decompressions of 30 min or more have progressively higher decompression risks (Weathersby et al, 1985; Thalmann, 1985).

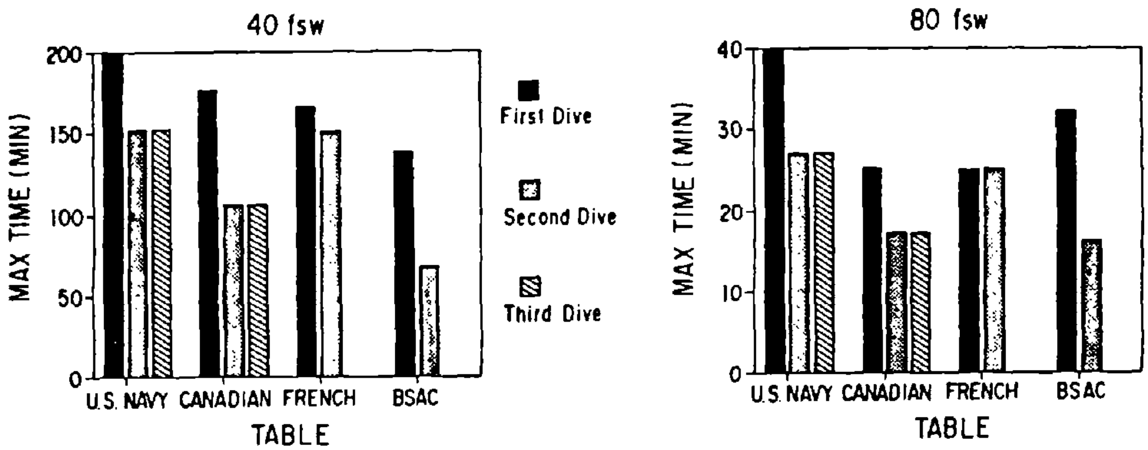

Figure 10. A comparison between no-stop repetitive dives to 40 and 80 fsw with a 4 hr surface interval for the U.S. Navy, Canadian, French, and BSAC air decompression tables.

The safety of the important repetitive dive tables is an even greater mystery. The Navy repet tables appear overly conservative for one or two repetitive dives with Repetitive Groups near the beginning of the alphabet, but multiple repet dives, particularly over many days, may lead to increased risk (Thalmann, 1985).

The uncertainty concerning both single and repetitive dives is illustrated in Fig. 10. The no-stop repet dive limits for 40 and 80 fsw dives with 4 hr surface intervals are compared for the U.S. Navy, Canadian (UDT, 1987), French, and the older BSAC (Hazzard, 1980) tables. The height of each bar represents the maximum no-stop exposure limit. The solid bar in each table grouping indicates the first dive, the diagonally-hatched bar indicates the second, and the cross-hatched bar indicates third and subsequent dives. The agreement between tables is not striking, particularly for repet dives. Both the Navy and Canadian tables allow multiple repetitive dives of equal length for the same surface interval. The French and BSAC tables, however, consider more than one repetitive dive to be unsafe. The surface interval after which a second dive is no longer repetitive is 12 hrs for the French and Navy tables, 16 hrs for the BSAC tables, and 18 hrs for the Canadian tables.

Each table has a different method for finding repetitive dive bottom time. The Canadians use a modification of the Navy procedure, the French provide a separate table for each surface interval, and the BSAC uses an average of the first and second dive times weighted according to surface interval. There is little question that a shorter dive is safer, but how short is safe enough? When dealing with risks of less than 1%, individual susceptibility may be more important than a small change in bottom time. At present, data are insufficient to determine which repetitive dive method is safe enough but not overly conservative.

While decompression tables will be with us for a long time, the ultimate solution for repetitive diving is the diver-worn decompression computer. As with any decompression procedure, however, DCS risk is greater for certain types of diving and depth-time ranges. The Divers Alert Network is currently studying the nature and risk of diving with both tables and computers. Table 3 shows preliminary results of this study for 38 computer cases and 91 computer and table cases. Dive profiles were examined in 4 categories: No-stop or decompression; square or multi-level; single or repetitive; and single-day or multi-day. For both computers and tables, decompression sickness was twice as frequent for repetitive and multi-day dives as for a single or single-day dives. Since the first dive of every repetitive dive is a single dive and the first day of every multi-day dive is a single-day dive, repetitive and multi-day dives are significant risk factors.

This observation appears contradictory to the effect known as "adaptation" in which DCS risk is decreased by daily pressure exposure. Adaptation was best documented in caisson workers exposed to relatively low pressures for up to 8 hrs (Walder, 1968). The most widely accepted explanation for adaptation is that daily pressure exposure depletes the nucleation sites from which bubbles form (Vann, 1987). A more recent explanation argues that decompression sickness is mediated by bubbles which activate the complement system and that depletion of complement during repetitive diving leads to reduced DCS susceptibility (Ward et al, 1987).

Multi-day diving differs from caisson work in that pressure exposures are shorter, deeper, and more frequent. Such diving may lead to an accumulation of bubbles which require longer than 12 hrs to be absorbed. It is for this reason that the BSAC and Canadian tables have adopted 16 and 18 hrs as the surface interval to clear the effects of a previous dive. An alternative explanation is derived from animal experiments which demonstrated that venous bubbles in the alveolar circulation can pass through the pulmonary filter and enter the arterial circulation during repetitive diving (Gait et al, 1975).

Table 3 indicates that bends are more common during square rather than multi-level dives for both computers and tables, but more multi-level bends occur with computers. The greatest difference between computers and tables is that decompression sickness occurs more frequently during decompression dives with computers and more frequently during square dives with tables. One explanation for this observation argues that divers are more likely to decompress when using a computer. Another

Table 3. Preliminary analysis of DCS cases collected by the Divers Alert Network.

	Computer Only 38 Cases ('84-'87)	Computer & Tables 91 Cases ('87)
Multi-Day	66%	70%
Repetitive	84	67
Multi-Level	47	27
Decompression	71	27

explanation holds that the decompression risk is greater for table diving because the no-stop limits are longer.

Without knowledge of the number of dives conducted, a distinction between these explanations is difficult. Fortunately, this knowledge, which is essential to the assessment of DCS risk, may be available in the future with the help of the decompression computer used as a depth recorder. Figure 11 shows a dive profile recorded during a Divers Alert Network Doppler research trip by a Suunto decompression computer made in Finland. The dashed line is the profile which the diver recalled from memory. The actual profile read from the computer memory is shown by the solid line which was drawn from depth-time points recorded at 3 min intervals.

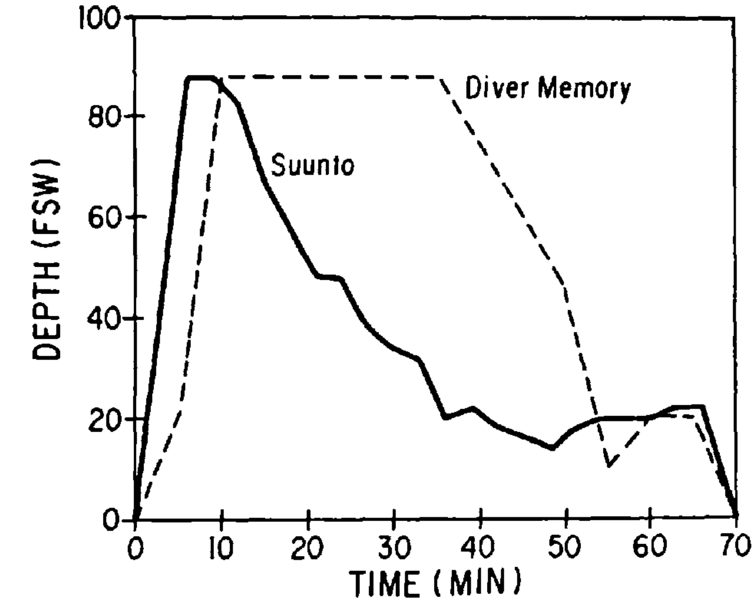

Figure 11. Dive profiles recalled by a sport diver and stored in a Suunto decompression recorder/computer. From data taken during a Divers Alert Network Doppler research trip.

Dive profiles of this nature and the results of both safe and unsafe dives can now be analyzed for decompression risk by a statistical method known as maximum likelihood. This method can be used to determine how well a decompression model explains the results of a dive series, and thus, it allows a quantitative comparison between models. The most successful model I have yet found assumes that before bubble formation, inert gas exchange is limited only by blood flow while after bubble formation, gas exchange is limited by both blood flow and diffusion (Vann, 1986). In Fig. 12, diffusion resistance is imposed by a diffusion barrier surrounding the bubble.

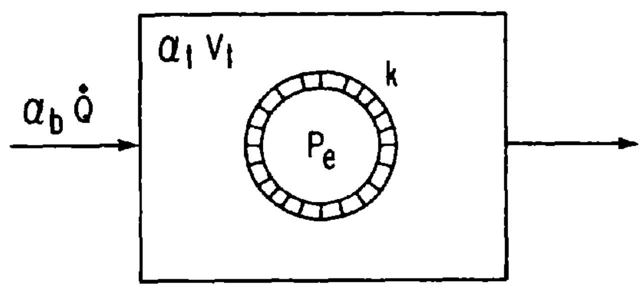

Figure 12. A decompression model simulating blood flow limited inert gas exchange in tissue and diffusion limited inert gas exchange in a bubble (Vann, 1986).

Such a representation of gas exchange makes it possible to predict the frequently observed delayed onset of DCS symptoms. This delay is illustrated in Fig. 13 for a 60 min air dive to 150 fsw. Most decompression models, including the Haldane model, predict that the greatest decompression risk occurs immediately upon surfacing. When bubble growth is limited by diffusion, however, the maximum risk occurs in the post-dive period--2 hrs after surfacing in the example shown here. Since bubble resolution as well as growth is limited by diffusion in this model, a bubble could persist and expand during a series of multi-day dives. This might explain the increased risk observed during multi-day diving.

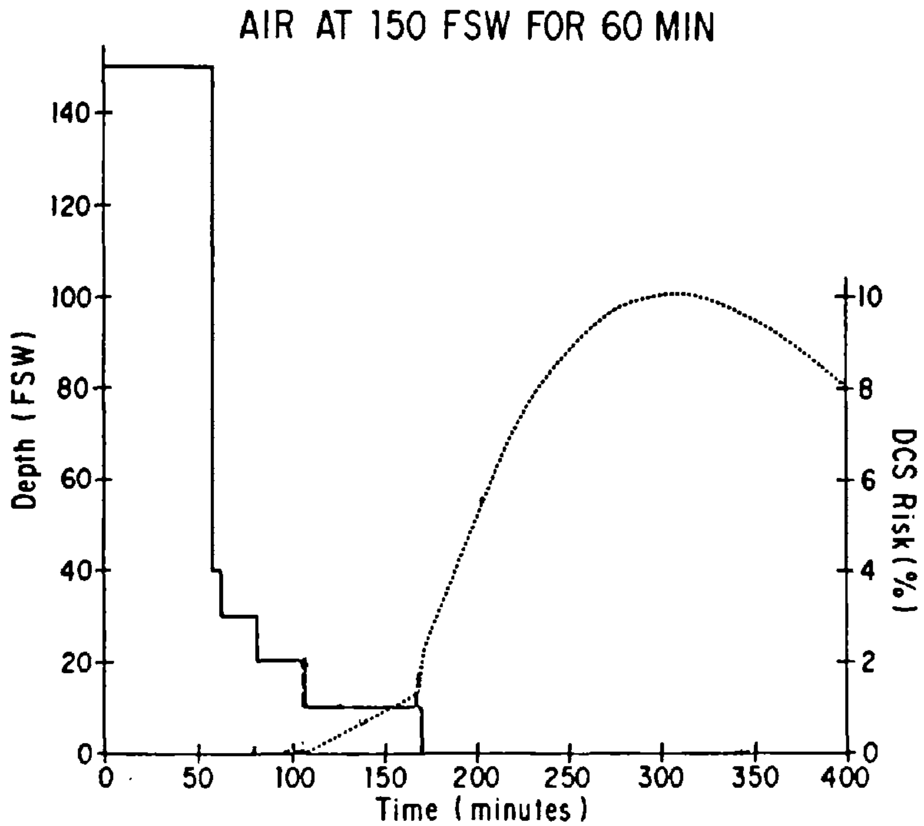

Figure 13. DCS risk after a 60 min air dive to 150 fsw as predicted by a decompression model in which gas exchange is blood flow limited in tissue and diffusion limited in bubbles (Vann, 1986).

CONCLUSION

The most effective method of increasing decompression safety and efficiency is the judicious use of oxygen. Oxygen-enriched air, supplied either as a constant percentage or a constant partial pressure, is equally useful in reducing nitrogen uptake at depth, but a constant partial pressure mix is preferable during decompression as it allows faster nitrogen elimination. Alternatively, 100% oxygen breathed during the shallow stops will provide the greatest decompression safety and shortest decompression time.

Experimental evidence pertaining to the validity of the EAD theory is mixed and further study is certainly warranted, but evidence from human studies does not contraindicate its use in unmodified form, at least up to an oxygen partial pressure of 1.3 atm.

The most significant problem for nitrox diving is a lack of confidence in existing decompression tables, particularly repetitive dive methods. The solution to this problem lies in empirical testing and statistical analysis. Dive computers are expected to play an important role in decompression procedure validation through their data logging capability and to provide a practical solution to the thorny issues of repetitive and multi-day diving.

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APPENDIX TO DR. VANN'S PAPER

Vann RD, Dovenbarger J, Wachholz C, Bennett PB. 1988. DCS and decompression meters. Undersea Biomed Res 15(Suppl):64.

101. DCS AND DECOMPRESSION METERS. R.D. Vann, J. Dovenbarger, C. Wachholz, P.B. Bennett. Hall Lab & Anesth. Dept., Duke Medical Ctr., Durham, NC.

38 DCS incidents with decompression computers were reported to the Divers Alert Network. 33 involved males (mean age 37 yrs). 5 involved females (mean age 36 yrs). 8 had pain, 11 had serious symptoms, and 19 had pain and serious symptoms. Dive profiles were categorized as: no-stop or decompression; square or multi-level; single or repetitive; single or multi-day; maximum depth on day of incident. Individual risk factors were examined. DCS increased with depth, decompression, repetitive, and multi-day diving. Individual risk factors were prominent in the least stressful categories. Dives in the upper left corner of the table may have been safe or may not have been conducted.

Max Depth	<60	60-69	70-79	80-89	90-99	100-109	110-119	120-130	>130
NoStpSquare									
DecomSquare									2(1*)
DecomMltLev							1*	1*	
NoStpMltLev				1(1)+					1(1)
NoStpRepet	1*				1*&(1)				
NoStpMltRpt			1(1)*		2(1*)	1(1)		1(1)	2(1*)
DecomMltRpt				3(3)&	1(1)	1(1)		1(1)%	1*(1)
DecomRepet		1(1)*		1*&(1)	2(1)	4$(3)	1(1)	2	5(2)

Risk factors:

() - 25 multi-day dives
* - 14 two incidents in same diver (high susceptibility)
& - 8 back trouble (spinal stenosis, diskectomy, fracture, etc.)
$ - 4 CNS disease or previous injury at DCS site
+ - 1 vestibular DCS with a history of vestibular trouble
% - 1 obesity

Discussion following Dr. Vann:

DR. VANN: An abstract for the 1988 UHMS meeting which gives a little information about decompression sickness and diver-carried decompression computers is included as an appendix to this paper. This particular abstract does not do a comparison with tables but it looks into the effect of depth.

Also, we took into account the individual risk factors which, as I indicated, seem to be important for very low risk dives.

DR. LAMBERTSEN: In the course of investigating the role of oxygen, dissolved oxygen in tissues in relation to whether decompression sickness occurs, one has to distinguish between whether bubbles are going to form anyhow; in other words, the nature of the decompression itself. Is that not right, that there is an inert gas component? It is not just oxygen that the animals are being exposed to?

DR. VANN: That is correct, yes, but it is the total dissolved gas situation that is important, oxygen plus inert gas plus CO_2.

DR. LAMBERTSEN: You are exactly right. Now, if you then recognize that and want to investigate whether oxygen actually can produce bends, not just contribute to whatever bends have happened, that is a different situation, is it not? Are there not two separate circumstances?

DR. VANN: It is sort of a compendium, but I think I would agree with that end of your compendium.

DR. LAMBERTSEN: If you wanted to see if there is such a thing as "oxygen bends", which is what the terminology says....

DR. VANN: Donald's term.

DR. LAMBERTSEN: That is what I said. We must not repeat something that is not right. Oxygen would be a certain thing if you were to compress on oxygen and stay there for a time and then decompress on oxygen to see whether you got oxygen bends. If you then wanted to find out if you got some influence of oxygen on bends, you would do a mix situation. Most all of these, as I see them, are mixed gases, are they not?

DR. VANN: Absolutely.

DR. LAMBERTSEN: I am trying to bring out here that if you want to talk about oxygen bends, then it ought to be oxygen. To do that you would end up producing oxygen poisoning, and you would be decompressing an oxygen poisoned animal, because you have to go to very high O_2 pressures to do that.

What I was saying is that there has not been a pure situation; if we are going to talk about oxygen bends, we ought to know what we mean and make sure it is oxygen. Then when you get through doing the experiment, you should be able to separate it from the oxygen poisoning. That is the kind of experiment that is needed.

DR. VANN: I think the experiment that is needed is to look at EAD theory, and most profitably and most importantly to do it in humans. Regarding the terminology of whether you call it oxygen bends, EAD theory, or whatever, we know what we are talking about, the concept of "Does oxygen contribute?" at this or that partial pressure. That is the issue.

You are right. The term oxygen bends has confused people, because people have generally said that any increased oxygen partial pressure is a problem. I think Ed Thalmann did this; he jumped on the Eaton and Hempleman data, and because of that he put it into his model. Whereas, if you look at all of the data, they are so scattered that, as Jim pointed out, you can go any way you wish. But if you look at the human data and particularly the study by Weathersby--who expected, I think, to find a bad EAD effect there--the best evidence just does not support it.

DR. LAMBERTSEN: I think that is a good way to state the circumstances with a mixed situation of oxygen and inert gas. So where we are at the moment, then, with this discussion is that nobody has done a demonstration of oxygen bends. There have been many studies in animals and some examinations of human decompression with mixed oxygen and inert gases, and you do not find anything there, statistically. Isn't that what you just said?

DR. VANN: Yes. And I think what you are doing is to correct a historically incorrect semantic term.

DR. LAMBERTSEN: That is the idea. Now we have gone two thirds of the way through the story, okay.

The next third of the story is, as I pointed out to you before, whenever you expose someone, animals or otherwise, to oxygen at very high pressures, you actually create a tissue hypercapnia. This then does things to the whole of the body physiology that are so complicated and uninvestigated that you cannot just say that we have just examined an effect of physically dissolved oxygen on bubbles, when the events that have been produced by oxygen at high pressure are multiple events and not just increases in physically dissolved oxygen.

DR. VANN: That is true, but you should not fall into our own oxygen trap. It is a function of the PO_2 itself. At low PO_2's there is very little difference and the higher you get, the greater that effect will be.

DR. LAMBERTSEN: If you again want to say that oxygen may influence the factors that lead to bends, then the story becomes a little more accurate; but to call it oxygen bends or bends aggravation by physically dissolved oxygen, that is not right. You have to really watch out for that one or else the experiments get designed wrong.

MR. GALERNE: I have a question. Can you tell now the possibility of CO_2 participation in bends?

DR. VANN: Well, there is a recent study that I think examined that effect. This was done over in England; it was called "Islander," I believe. They were looking at nitrox/air saturation, at 25 fsw give or take a few feet, and they did it with CO_2 and without CO_2. I can not remember, was it 2% CO_2, Claude?

> Reference: Bell PY, Harrison JR, Page K, Summerfield M. 1986. An effect of CO_2 on the maximum safe direct decompression to 1 bar from oxygen-nitrogen saturation. Undersea Biomed Res 13(4):443-55.

CAPT HARVEY: They had a couple of different levels.

DR. VANN: In any event, they did not find any increase in bends as a result of CO_2. The implication was there that there may have been fewer intravascular bubbles with CO_2, but the changes were so small that you could not really draw any significant conclusion.

There is a lot of information in the old literature, particularly from tunnel work, concerning the effect of CO_2 on bends which says, yes, it is important, and then this study says, no, it is not important. Perhaps it is a condition of the situation. Perhaps it does not make any difference.

DR. HAMILTON: You do not know what else is going on in addition to the higher CO_2. There is really no causal relationship that has been shown.

DR. VANN: Correct.

DR. HAMILTON: The British group did an experiment that tried to clear everything else away and look at just that, and I thought it was pretty good.

DR. VANN: Yeah, it seemed to answer the question.

DR. HAMILTON: On the slide in which you showed Weathersby's data, with no EAD deviation at all, you showed some points by Logan. If I recall what you said, they were something like two out of six or four out of six.

DR. VANN: One out of five and two out of five.

DR. HAMILTON: That is not a difference. You cannot draw that kind of a line and compare it with Weathersby's data on that.

DR. VANN: I think that is true. That is right.

DR. HAMILTON: Weathersby used lots of dives, and furthermore he was trying to find a difference.

DR. VANN: He was trying to find it and was disappointed when he did not find it.

DR. HAMILTON: That is the best evidence. All of the rest of the evidence you more or less dismissed, did you not?

DR. VANN: Well, you know, something is going on, and certainly the higher the PO_2, the more oxygen is likely to have an effect.

DR. HAMILTON: That is what Dr. Lambertsen said, because oxygen is a poison or a very physiological substance. We do not know enough about what it does at 2 atmospheres. The effect may be more one of physiology than its acting as an inert gas.

CAPT HARVEY: I would like to reemphasize something that you said in the paper, because I think it is important. We are looking at a relatively new (or revised) technique in using this enriched air or oxygen additive or whatever you want to call it. When we do that and we use the EAD concept, we are now relying on tables which have incidences of bends associated with them. We do not know what that incidence is.

With the Navy tables, frequently they do not dive them right up to the mark, if you will. Particularly if there is hard work done or cold exposure, they will "slide" a table.

So when you try to analyze the statistics, it is very difficult to really say what the bends incidence is for any given Navy table. I would caution everyone not to blame the technique of adding the oxygen. If we start seeing decompression sickness or a problem, remember the table itself may be the problem that you are finding. Keep that in mind.

DR. VANN: The evidence indicates that the problems are going to be with the tables, not the EAD theory.

MR. NISHI: I would like to comment on what you said about the bubble intensity increasing at about a 2 hour maximum.

DR. VANN: That was just in a particular example.

MR. NISHI: From some of our doppler studies we find that bubbles do not appear right away and we get the maximum bubbles about one to two hours after a dive. So this might correlate with your calculations.

MR. RUTKOWSKI: I do not know if this is the time or the place, but if possible, could you just comment a little bit on the status and the validity of the new PADI 60 minute half time "tissue" for repetitive dives?

DR. VANN: As you said, this is neither the time or the place.

DR. HAMILTON: Come on, it is a good time and a good place. Go ahead.

DR. VANN: No, I am not going to say anything about that. There are a couple of issues that are being sorted out, and this is not an appropriate time to discuss it right now.

MR. RUTKOWSKI: I just thought maybe we could catch you in a weak moment.

DR. VANN: Nice try.

DR. CROSSON: What would you say would be the next major step for looking at it (enriched air nitrox) in the broadest scope, looking at research?

DR. VANN: Well, I have a modest proposal that I plan to make. I do not know if I should discuss it this widely but I think there is a lot that can be done. I think we are perhaps at the right moment in space and time to make some improvements and some changes and perhaps this group will catalyze it. I mean, basically, let's see what we can do to improve decompression safety and efficiency by using oxygen-enriched gas mixtures, oxygen enriched air. I think a lot can be done. As to your specific program, I have some ideas in mind but I really want to think about it a little bit more before commenting.

AIR AND NITROX DIVING: EXPERIENCES IN THE U.S. NAVY

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ABSTRACT

Harvey CA. 1989. Air and nitrox diving: Experiences in the U.S. Navy. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research.

The U.S. Navy does not currently use enriched air nitrox diving techniques of the type under discussion at this Workshop. However, certain special types of diving apparatus provide non-air nitrox mixtures and require decompression techniques different from the standard air tables. The Mark 6 uses different mixtures of oxygen and nitrogen, all with greater oxygen than air; decompression techniques for the Mark 6 use the Equivalent Air Depth method. Results of the use of this method within the Navy appear to be as good as those with the basic tables themselves. The Mark 16 uses a set level of oxygen, 0.7 atm, and uses special tables prepared using different criteria from those used to prepare the air tables. The Navy still uses oxygen tolerance tests but they are notoriously unreliable.

INTRODUCTION

Currently the U.S. Navy does not utilize what is commonly referred to as "enriched air" mixing and diving techniques that involve cascading oxygen into standard SCUBA bottles to increase the partial pressure of oxygen in the breathing mixture above that of compressed air. The Navy does however use nitrogen/oxygen as well as pure oxygen mixes in specialized diving equipment. Decompression procedures for such diving have traditionally relied on the concept of Equivalent Air Depth calculations.

Table 1. Normal working limits for pure oxygen diving.

Depth	Maximum Oxygen Time
25 fsw	240 minutes
30 fsw	80 minutes
35 fsw	25 minutes
40 fsw	15 minutes
50 fsw	10 minutes

The U.S. Navy uses open circuit SCUBA demand regulator equipment routinely with compressed air. This equipment is simple, but diving is restricted in terms of depth and time. Magnetic characteristics and production of bubbles further restricts some operational situations. Thus different pieces of equipment and techniques have evolved for specific tasks. All of these diving rigs have limitations based on avoiding hypoxia, oxygen toxicity and carbon dioxide poisoning. Decompression times, of course, must be controlled within the limits of the available gas supply in the tanks. Further the equipment is relatively complex to set up and maintain as well as expensive.

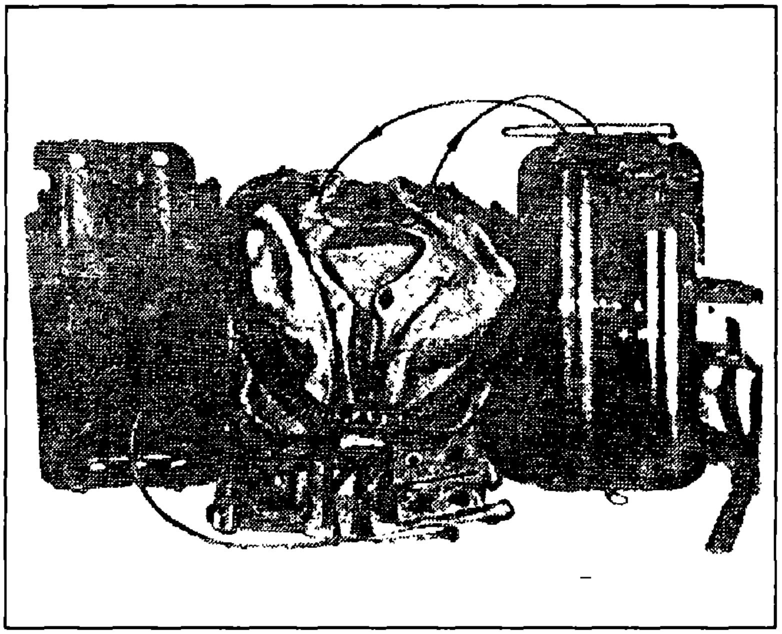

Figure 1. Pure oxygen rebreather. Arrows indicate rebreathing circuit.

One of the simplest in concept is the pure oxygen rebreather, (Figure 1), which is a closed circuit system. It is designed primarily for shallow-water and clandestine operations. Normal working limits for pure oxygen diving are shown in Table 1.

The possibility of sudden oxygen toxicity is the greatest drawback to this equipment but it is quiet and leaves no telltale trail of bubbles. The diver selects the rate of oxygen injection into the breathing system based on his work load. Thus he controls to some extent the duration of his gas supply. Pure oxygen dives also avoid any possibility of decompression sickness, although gas embolism can still occur and flooding of the carbon dioxide absorbent canister is an additional hazard.

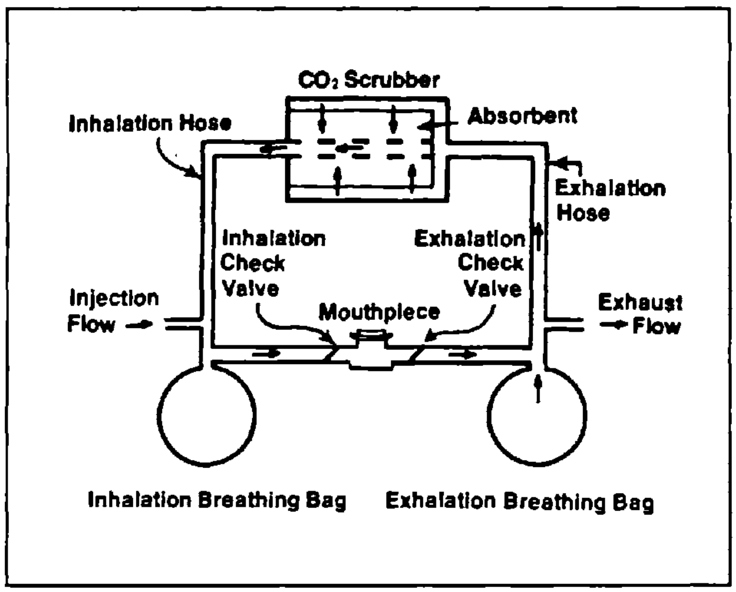

Figure 2. Schematic of the basic UBA recirculating loop.

For deeper dives, with longer durations, semi-closed equipment (Figure 2) is available which depends on a supply of breathing gas consisting of nitrogen mixed with a greater percentage of oxygen than air contains. The Mark 6, which is being phased out of use by the U.S. Navy, partially recirculates the divers breathing gas to remove carbon dioxide while simultaneously injecting and exhausting enough gas from the tanks to furnish oxygen sufficient for metabolic requirements. The breathing gas injection rates must be selected before the dive. The proper nitrogen/oxygen breathing gas must also be mixed and the tanks filled with it. Thus considerable planning and knowledge for each dive is necessary. This approach does give efficient utilization of the mixed-gas supply. The Mark 6 can be set up for any one of three different gas mixes: 60% oxygen and 40% nitrogen; 40% oxygen and 60% nitrogen; 32.5% oxygen and 67.5% nitrogen. The breathing mixture is chosen for a particular dive to insure that the oxygen level in the breathing bags at the maximum operating depth will never exceed a partial pressure of 1.6 ata. This diving system permitted normal diving working times as shown in Table 2. Proper control of inflation and purging of the breathing bags is part of learning to use this equipment in the water. Decompression is calculated in advance of the planned dive and uses standard air diving tables selected by air equivalent depth calculations.

The most advanced equipment to conserve the breathing mix and increase dive time is the closed-circuit Underwater Breathing Apparatus (UBA), Figure 3. Essentially this diving rig has a closed loop filled with a mixture of inert gas and oxygen at a set partial pressure, which is 0.7 ata in the current Mark 16 UBA. Oxygen sensors then automatically add oxygen to the system as it is used and carbon dioxide is removed chemically by an absorbent. This rig in its antimagnetic form is ideal for dives demanding long bottom times at depths where thermal and decompression considerations become the limiting factors of endurance. When used with nitrogen/oxygen this rig can be used to depths of 150 feet for 100 minutes of diving time. A wrist mounted decompression meter preset to calculate for dives using 0.7 ata of oxygen and variable depth profiles is under development. It will not use air equivalent depth calculations but will be based on experimentation and mathematical models developed at the U.S. Navy Experimental Diving Unit and the Naval Medical Research Institute. One computation method under consideration (Thalmann, 1985) states that the decompression model uses total gas tension in determining decompression stops and computes a venous oxygen tension from an arterial value based on the hemoglobin dissociation curve and an assumed tissue

Table 2. Mark 6 normal diving working times.

Mixture	Maximum Depth, fsw	
	Normal Exposure	Exceptional Exposure
60% O_2, 40% N_2	55	77
40% O_2, 60% N_2	97	131
32.5% O_2, 67.5% N_2	129	170

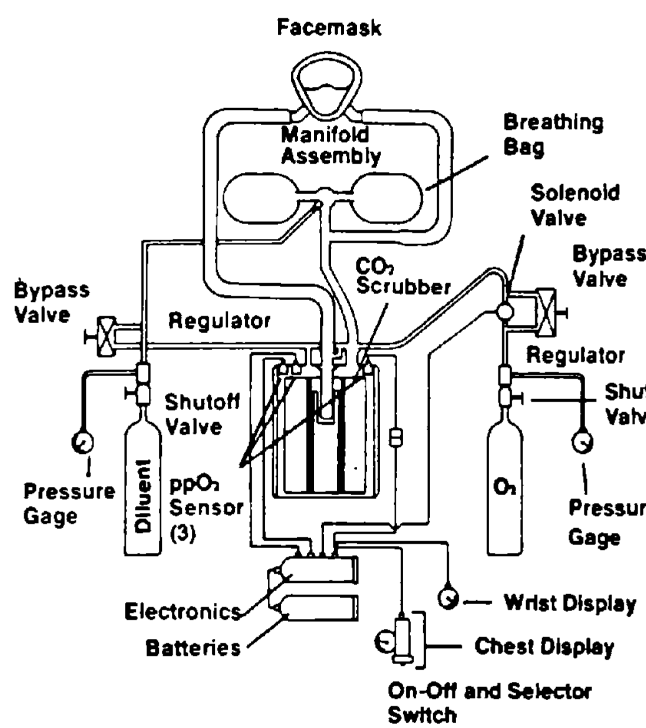

Figure 3. Flow diagram of a typical closed-circuit UBA.

metabolic rate. Gas uptake is assumed to be exponential in the usual way, while offgassing is assumed to be exponential until a gas phase is present and linear thereafter. This model computes for 9 different half-time tissues. Another method under consideration calculates tables based on the maximum likelihood techniques (Weathersby et al, 1984; Weathersby, Survanshi et al, 1985; Weathersby, Hays et al 1985).

Obviously all of these approaches satisfy the U.S. Navy's needs for reliability, versatility and unique military tasks. Each new technique and piece of equipment undergoes extensive testing and evaluation before approval for fleet use. Figure 4 shows a schematic of the kind of test set-up typically used to test new equipment (Gray and Thalmann, 1980). The performance of various masks, work loads, gas mixtures, temperatures, and other variables are then tested before any diver ever puts on the gear. If the rig or procedure meets design criteria, human tests are next, again using sophisticated test equipment and procedures. Finally training, certification, maintenance and operational limits are established. Then, the gear is released for fleet purchase and use. The procedures are slow and expensive, but the divers can trust and know how to use their equipment.

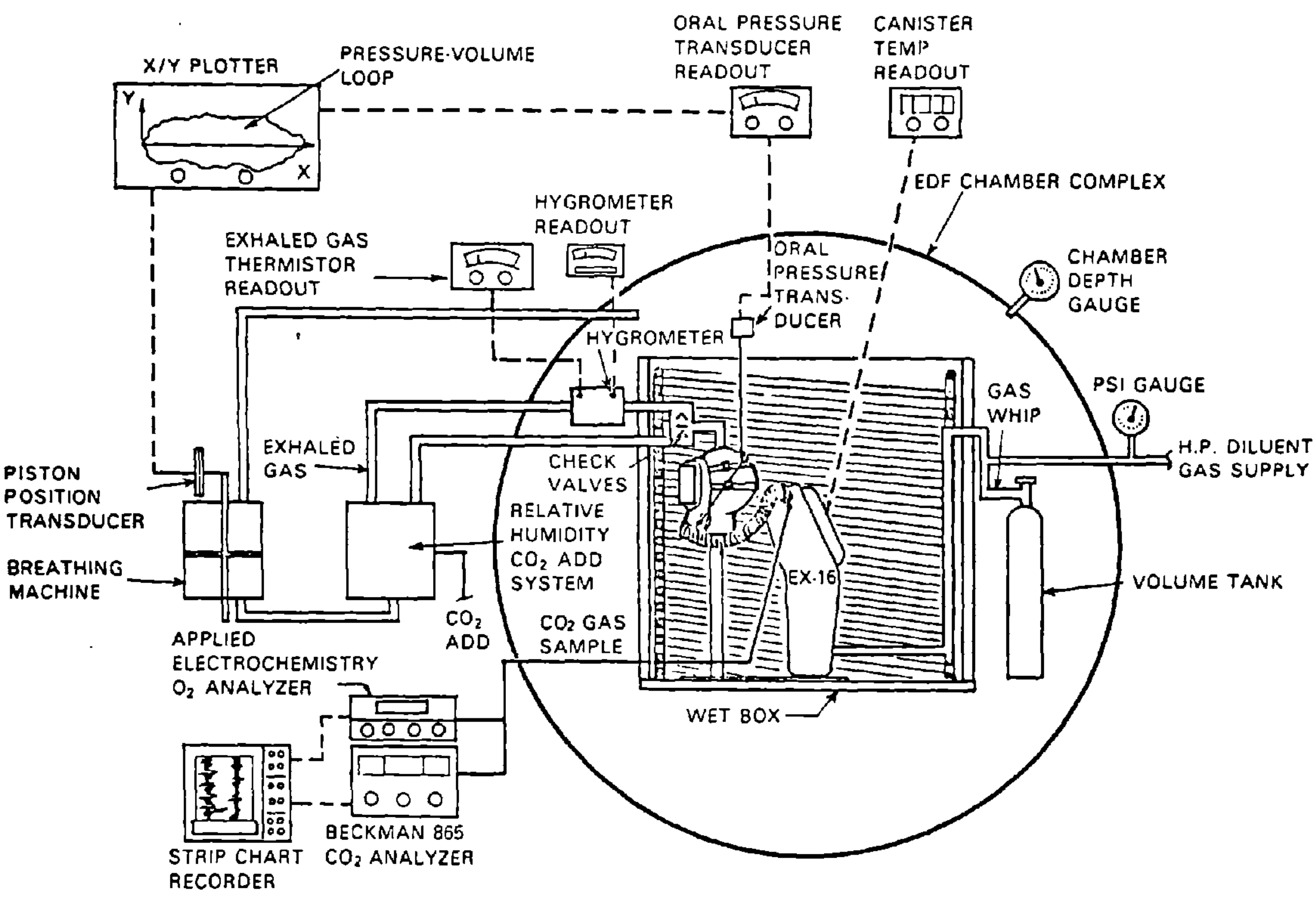

Figure 4. Schematic of test set-up typically used to test new equipment.

It is interesting to note (Figure 5) the increases in nitrogen non-decompression diving limits that can be derived from standard U.S. Navy air diving tables and converted for various nitrogen-oxygen mixtures (Dwyer, 1955). The mathematical derivation of such increased limits is relatively easy. Those familiar with the testing of such calculated limits know that the vagaries of human physiology do not always follow mathematical predictions. Thus due caution and observance of other limits such as those imposed by oxygen toxicity must be considered and tested adequately before one places blind faith in such predictions.

Dr. Flynn compared (Table 3) the gas supply requirements of various types of breathing apparatus in use by the U.S. Navy. He assumed a ventilation rate of 3 liters/min STPD and calculated gas consumption at the surface and at 297 fsw for comparison purposes, although some of the rigs are not approved for that great a depth (Flynn et al, 1981). The advantages of semi-closed and closed systems in gas savings are obvious.

Table 3. Gas supply requirements of various types of breathing apparatus in use by the U.S. Navy.

Apparatus	At Surface	At 297 FSW
Open-circuit		
Mark V Air	152.0	1520.0
Demand SCUBA	69.0	690.0
Semi-closed-circuit		
Mark VI SCUBA	10.5	105.0
Mark V Helium	14.0	140.0
Closed-circuit		
Emerson Rebreather	3.0	3.0
Mark X (Closed System)	3.0	3.0

U.S. Navy experience with the use of the Equivalent Air Depth concept with the Mark 6 semi-closed diving equipment has been satisfactory. However, the equipment is not used for dives below the 130 fsw range very often and thus there is little data on which to predict the success of using enriched air for deep dives followed by EAD calculated decompression using U.S.Navy air tables. A few individuals have collected data from proprietary sources that enable them to use or modify the Haldanian model to predict safer tables than those in the exceptional exposure ranges for air diving in the U.S. Navy Diving Manual. However these calculated and relatively untested tables should be used only with caution, and certainly the current exceptional exposure tables should not be used for EAD diving. Extrapolation of the regular air tables to support EAD decompression should be done with caution, particularly in the deeper or longer dive areas of the tables.

Oxygen tolerance tests are notoriously unreliable. Nothing better is available and they probably pick up individuals who are exceptionally sensitive to oxygen at least some of the time. I recommend them for divers who are going to be diving with gases containing high partial pressures of oxygen. A convulsion deep underwater is not a pleasant thing to deal with.

Repetitive diving tables are easy to calculate and computers can produce them based on input from a pressure transducer. However, until extensive diving is done to test the mathematical assumptions of a computer model, caution should be applied when using the results. This is true

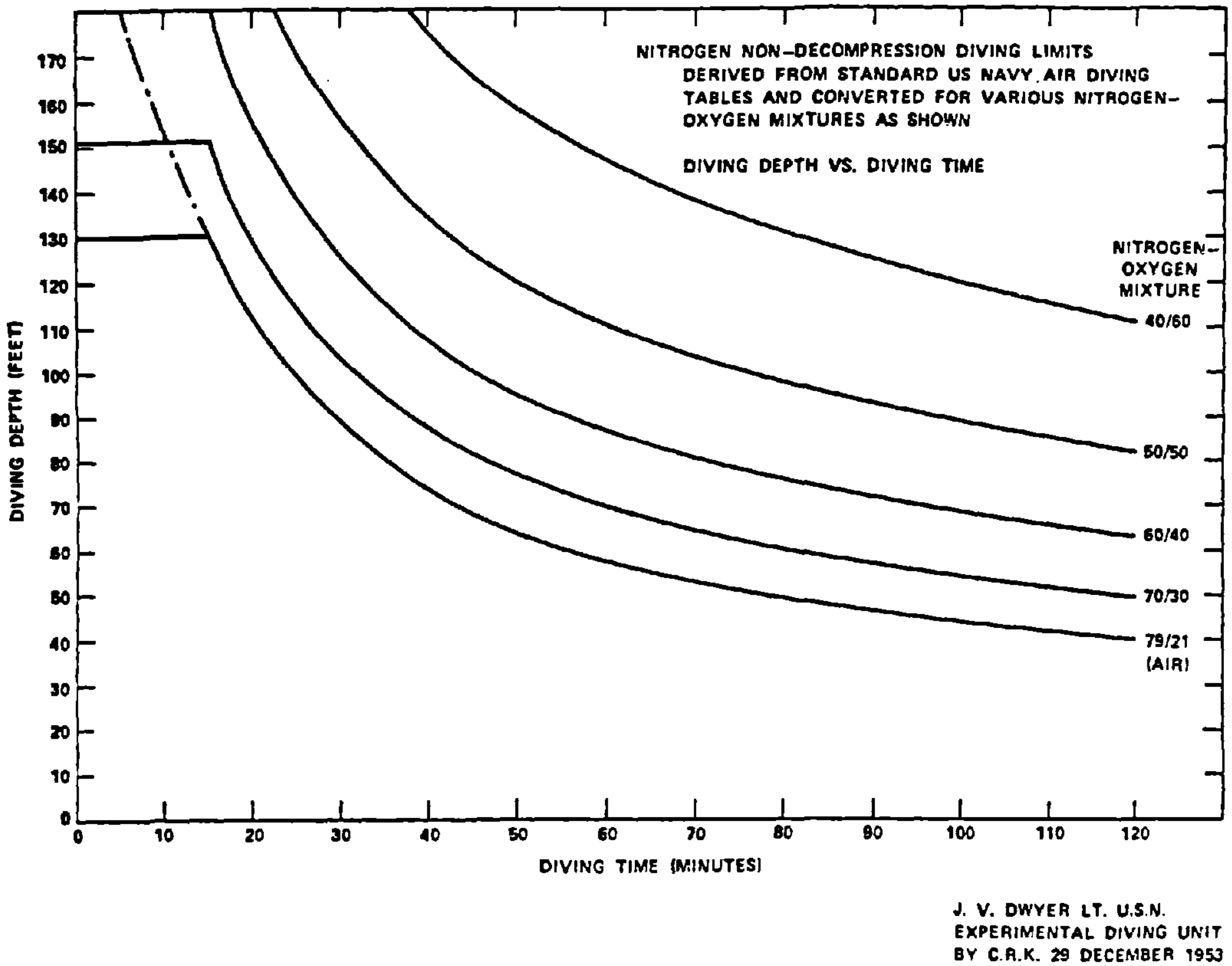

Figure 5. Nitrogen non-decompression diving limits (Dwyer, 1955).

not only for variable depth profiles but for repetitive diving calculations where few really accurate data banks of dives are available for analysis. The probability methods now being explored by Dr. Paul Weathersby probably offer the best hope for developing models that will enable computers and divers to move more safely into these areas and away from the restrictions of the conservative U.S. Navy repetitive diving tables (Weathersby, Homer et al, 1984; Weathersby, Survanshi et al, 1985; Weathersby, Hays et al 1985).

In summary, the use of "Enriched Air" or Nitrox with a partial pressure of oxygen higher than compressed air has been shown to be a viable technique to increase working time at relatively shallow depths without incurring additional decompression obligations. The concept of EAD decompression is valid, but limited by the reliability of the air tables themselves. Great care must be taken to mix nitrox safely and to specifications. The equipment and procedures used should be actually proven capable of supporting the technique, not just theoretically proposed before release from the research and development arena to the general diving public.

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The views, opinions, and/or assertions herein are those of the author and should not be construed as official or reflecting the views, policy, or decision of the Navy Department or the Naval Service at large.

Discussion following Capt. Harvey:

CAPT. HARVEY: The Navy is not doing the kind of diving that we are most interested in here, i.e., enriched oxygen air equivalency diving. We have done something somewhat similar to that.

We also made passing reference to different kinds of tables and different kinds of gear and what have you and have referred to the Mark 6 and so forth.

First I would like to show you the kind of diving that the Navy is doing now to put this into reference a bit.

DR. HAMILTON: Did your analysis go far enough back into history to determine where the Navy got this 0.7 atm PO_2 for its closed circuit rebreather, and why do they stick with it?

CAPT. HARVEY: It was, I think, the projection that would keep us out of any central nervous system toxicity at the depths that we particularly wanted to go through with this rig.

DR. HAMILTON: But it is independent of depth.

CAPT. HARVEY: It is independent of the depth; but if they had to go to emergency use of the air and stuff that was with it, we considered that as one of the limits in setting it and I think that influenced the choice of the 0.7 PO_2.

DR. HAMILTON: Oh, so you do not really know a reason why they stuck with it when it is so difficult to decompress from 0.7 PO_2, especially when nitrogen is the gas?

CAPT. HARVEY: No. We wanted to use a totally closed system. I do not know why we stuck with that to the exclusion of using other oxygen levels. I have no good answer for you.

DR. LAMBERTSEN: I think Claude is right. It was probably chosen by an individual in the laboratory, not by the Navy, right?

CAPT. HARVEY: Yes.

DR. LAMBERTSEN: And in the laboratory that was doing it, it did not have to include all of the thought that someone else might have put in.

DR. VANN: Here may be your answer right now.

MR. RICCIO: It was based on work load, not decompression. Early on in the development of your closed circuit oxygen diving a level of oxygen was picked to go with not too high a work load. We picked a level where the work load demand for oxygen would not be so high as to get the divers in trouble, but not so low that he would be in the low range. So we picked an average work load of a diver really doing work and picked out a level in atmospheres from Bioastronautics Data Book at the time. That was back in 1969. We felt that was a good level not to get him in too much trouble at the time. That is what was known. Since then elevated PO_2's have been shown to be better in decompression, but they have stuck with the 0.7 atm. I do not know why they stuck with it but they did. That is where it came from, just a higher level of oxygen at a work rate.

CAPT. HARVEY: Once you start building a body of knowledge based on decompression, it becomes hard to switch. So I think we got ourselves far enough in with all of the money we invested in these tables that it was difficult to switch.

MR. RICCIO: But at the time we did some deep studies with the unit being modified, which is now called SCCR 15.

In Norway two years ago they elevated the PO_2 to 1 atmosphere for a chamber dive to 1400 fsw. So there has been work in very deep depths.

DR. LAMBERTSEN: Claude, I think what Lou said is right, but it still is the same answer, is it not, that essentially one or two people made a choice? It was not done by a careful judgment of all possible aspects of the mission and so forth, because at that point in time far more was known than necessary to choose higher levels, you see. Isn't that right?

It just happened to be for other reasons that the individuals involved wanted to put an anchor where they did, even if it were possible to do higher levels and shorten decompression. It was simply normal decision making for certain purposes at that point in time. Isn't that so?

MR. RICCIO: That is right.

DR. CROSSON: On the use of tables for air-equivalent diving, I think it has been pretty well discussed here that in reality the limiting factor in many cases still will be the tables themselves. I see that no-decompression levels are going to be extended in certain areas. Bill Hamilton has certainly shared the fact that he feels very comfortable with the Navy's no-decompression limits.

CAPT. HARVEY: Whenever you start dealing with repetitive diving as you try to extend the no-d limits, when you put your residual nitrogen time on, you run into problems. So the no-d limits get shortened based on that pressure, rather than the initial testing of the no-d limits.

DR. CROSSON: That was going to be my question. Given that that would be the reasoning, is it still the fact that if the Navy is developing these tables, they are still truly looking at Navy needs and not the fact that a lot of other people are using the tables?

CAPT. HARVEY: You are absolutely right. One of the burdens the Navy has carried over the years is that we would develop tables for certain use by a certain Naval population, then when other people adapted them for other uses sometimes they were not ideal, and then they would come back and say, "Navy, you are producing horrible tables." For our purposes they were fine.

I would be quite interested in what Dick Vann would say about Weathersby's probability evaluations of the three tables.

DR. VANN: I think they are great. I think what Paul Weathersby has done is more valuable than anything that has come along possibly since the original Haldane approach. I am wearing a watch and I know what time it is. If I were wearing two watches, I would not be sure what time it was. My predictions are a little bit different from Paul's, but they are within a couple of percent. I do not think that is really the important factor.

What we have now is a way of using a great many different tests and combining them to give us an estimate of risk, and also a way to compare which approach to decompression is quantitatively more successful. So I see tremendous progress in the foreseeable future of five to twenty years in improving decompression safety.

I think one of the most important areas though, which was really started by Tom Berghage years ago and Paul has emphasized even more in his work, is that we are not dealing with an all-or-none phenomenon in decompression sickness. There is the consideration of risk. One of the toughest questions is what risk are you willing to accept as a compromise between safety and useful bottom time.

It is a very difficult question to answer. I think that abstract on DAN results indicates the greatest DCS risk is going to be concentrated in a few susceptible individuals, and there are also things that divers can do that can increase their risks one day and not another day. This follows from the tunnel work that has been done, too, that most bends occurred in a few individuals.

Now, how are you going to balance that against the guy we all know who goes out and dives well beyond the Navy tables and gets away with it all of the time, and then says, "Well, I do it, you know, so anybody can do it?"

There has to be a change in the appreciation of divers--all divers, I think particularly sport divers--that there is no magic depth and time limit that is going to eliminate the risk of decompression sickness. It is a question of education. It is a question of using some of the new techniques we have statistically, and it is a question of more empirical testing. We are making progress and I feel very good about it.

CAPT. HARVEY: I would toss out one other thought on that. You as operators when you are putting divers out there are choosing to use certain tables and certain techniques and certain pieces of equipment, and you must know what level of risk you are willing to accept. If you are going to do deep, long dives, the current state of the art is such that you are putting your people at greater risk. So you must then prepare to treat them and handle them if the risk does, indeed, become a reality. So you have to decide. Decompression theory people are not going to do it. You have to decide what risk are you willing to accept in order to get that job done and then plan adequately to support your people.

MR. GALERNE: There is no doubt in my mind that diving is like cold. Some people tolerate it and some do not. We have divers in our organization that we will never expose to deep water.

CAPT. HARVEY: On any given day they may get away with it but then they may not.

MR. GALERNE: Yes. There is a huge variation between divers. It is not a question of size. It is not a question of strength.

CURRENT DEVELOPMENTS IN CANADA REGARDING NITROX AND SEMI-CLOSED DIVING SYSTEMS

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ABSTRACT

Nishi RY, Eaton DJ. 1989. Current developments in Canada regarding nitrox and semi-closed diving systems. In: Proceedings: Harbor Branch Workshop on enriched air nitrox diving. Hamilton RW, Crosson DJ, Hulbert AW, eds. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research. [Also DCIEM No. 88-TR-07.]

The Canadian Clearance Diving Apparatus is a semi-closed circuit breathing apparatus in use by the Canadian Forces. This apparatus and its commercial version are designed for use to 55 metres of seawater using premixed gases. The decompression requirements for semi-closed circuit systems are generally determined from the Standard Air Tables using the equivalent air depth, and these procedures have been shown to be reliable. There are advantages and disadvantages of developing specific decompression tables based on the actual oxygen content in the counterlung. Such tables can lead to shorter decompression times and increased no-decompression capability, but they lead also to increased complexity and some uncertainty because of changing oxygen level. Other options exist for use of the CCDA in other operational modes such as umbilical supplied.

INTRODUCTION

Historically, the use of nitrox in the Canadian Forces has been restricted to mine countermeasures (MCM) diving apparatus. The Canadian Forces were originally involved with the Royal Navy MCM teams during World War II and until recently the apparatus used was the British designed and manufactured Clearance Diving Breathing Apparatus (CDBA). The CDBA is a semi-closed circuit system of World War II vintage. Because of supply and support problems, DCIEM was asked to develop a replacement for the CDBA in 1979.

The design of diving apparatus and techniques used for MCM have been molded by the mine threat. Underwater mines have sensing systems that are activated by motion, magnetic fields and/or sound. Sound was the most important factor in the original design of MCM diving apparatus as the gas escaping from an ordinary open-circuit diving apparatus created too much noise. As a result, closed and semi-closed circuit diving apparatus were used. Rebreathing gas in and out of a counterlung resulted in only a small amount of gas escaping from the apparatus. The escaping gas could be diffused into tiny bubbles which produced much less noise than in an open circuit system. Because the breathing gas was recirculated, with new gas being added to replace the oxygen consumed by the diver, the gas supply rates were much lower than with open-circuit systems. The result was a greater gas supply endurance and consequently longer dives for a given bottle size.

DEVELOPMENT OF THE CANADIAN CLEARANCE DIVING APPARATUS

In considering a replacement, several options were explored but it was decided to stay with a semi-closed circuit set based mainly on its relative simplicity in comparison to a closed-circuit design. This also would result in lower costs, maintenance, and higher reliability for MCM use.

The design of a gas control circuit was investigated and it was decided to use the circuit developed by Morrison (1978). Unlike conventional semi-closed circuit designs, this was a very innovative design with the circuit supplying a gas mixture of constant oxygen partial pressure (PO_2) to the counterlung from separate diluent and oxygen supply bottles. The oxygen and diluent were automatically mixed according to depth and, in principle, allowed the operation of the set throughout its design range without adjustment. Conventional sets typically require gas bottle changes and gas supply circuit adjustments for different depths. The design was also to increase the depth capability from the CDBA limit of 55 metres of sea water (msw) to 80 msw. Although nitrogen could be used as the diluent up to 55 msw, beyond this depth helium would be required to eliminate narcosis problems. A contract was let to the Nova Scotia Research Foundation in 1979 for the development of this set. Unfortunately, for a variety of reasons, several problems were encountered during the development of the gas mixing system. The original concept of developing a unit capable of operating at all depths between 0 and 80 msw was postponed. Subsequently, the project was then divided into two phases in 1984.

The first phase was to provide a 55 msw semi-closed circuit set to replace the CDBA. The concept was changed back to the more traditional design where oxygen or different premixed oxygen-nitrogen mixtures could be used depending on the maximum depth of operation desired. The basic breathing loop, developed under the original contract, was modified so that it could be combined with a traditional CDBA type gas supply system. However, the new apparatus has substantially upgraded life-support capability when compared to the CDBA. The redesign did not involve changing the gas mixtures or flow rates. In fact it was a design goal to keep these features the same. The major changes came in the form of a larger gas supply for increased endurance and a carbon dioxide scrubber which virtually eliminates the high inspired carbon dioxide levels that existed in the CDBA. The endurance of the scrubber has been rated at 120 min. This more modern version of the CDBA was developed by DCIEM and the present manufacturer, Fullerton, Sherwood Engineering Limited, and is designated the Canadian Clearance Diving Apparatus (CCDA). The civilian version of this apparatus is called the SIVA 55 by the manufacturer.

The gas mixture used in the semi-closed diving system was determined from a series of simple calculations based on a number of physiological assumptions (Royal Navy, 1987). These are shown in Table 1.

The minimum O_2 consumption was for a resting diver and the maximum consumption was based on a swimming diver wearing swim fins. These assumptions were used with two basic criteria to determine the concentration of oxygen in the supply gas mixture and the flow required to dive to a given depth. The criteria were to minimize the gas supply flow rate so that endurance was

Table 1. Physiological assumptions for CCDA semi-closed diving.

O_2 Partial Pressure:	0.2 ATA < PO_2 < 2.0 ATA
Minimum O_2 Consumption:	0.25 L/min (STPD)
Maximum O_2 Consumption:	3.0 L/min (STPD)

maximized and to maximize the oxygen concentration so that flowrate and decompression could be minimized. With these assumptions and criteria, an optimum flow and gas mixture could be calculated for every depth. However, operational logistics problems make it more feasible to have a few different gas mixtures that will cover a range of depths. Consequently, the gas mixtures and depth ranges shown in Table 2 were adopted for MCM diving with the CCDA. These are the same as those used with the CDBA.

The 60% and 40% oxygen mixtures are capable of supporting divers at metabolic rates of 3 L/min. However, the 32.5% O_2 mixture can only provide slightly over 2 L/min. To safely maintain a diver consuming oxygen at a rate of 3 L/min using this mix would require the flow rate to be about 20 L/min. Flow rates of this magnitude would seriously limit the endurance of the gas supply and make it very difficult for the diver to control buoyancy at shallower depths. With the flow rate of 13 L/min, the risk of hypoxia exists so that dives beyond 42 msw with the 32.5% O_2 mixture are intended to be only for visual inspection with no hard work involved.

Table 2. CCDA Flow rates and depth limits for MCM diving.

Mixture $\%O_2/\%N_2$	Mixture Flow Rate (L/min)	Oxygen Flow Rate (L/min)	Max. Depth (msw)
60/40	6	3.6	25
40/60	12	4.8	42
32.5/67.5	13	4.2	55

The CCDA should be going into service near the end of 1988. The commercial version, the SIVA 55, is expected to cost approximately $16,000 Canadian.

Phase 2 of the replacement project is the development of a set capable of operating between 0 and 80 msw. This second apparatus uses the same breathing loop as the CCDA with a new gas mixing system in which oxygen is mixed with a diluent, either nitrogen or helium. This unit, called the Canadian Underwater Mine Apparatus (CUMA), is designed for operation to 80 msw on helium and 55 msw on nitrogen, and supplies a constant oxygen partial pressure to the counterlung. During decompression, the diluent can be shut off so the gas control module provides 100% oxygen. The civilian version of this set is designated as the SIVA+ since the 55 msw gas supply system can be replaced with the 80 msw module.

DECOMPRESSION CONSIDERATIONS OF SEMI-CLOSED BREATHING APPARATUS

During the development of the CDBA replacement, a study of the depth limitations and the endurance of the different configurations made it clear that decompression requirements needed to be examined. Traditionally, decompression has been carried out by calculating the amount of nitrogen in the counterlung and working out the equivalent air depth (EAD). TheEAD was used to obtain the decompression schedule from the standard air table. An alternative possibility for decompression was to develop a set of tables specifically for use with the CCDA breathing apparatus. This would require actually measuring the PO_2 in the counterlung for a large number of dives and subjects to establish some PO_2 value on which to base the decompression requirements.

The calculation of the decompression requirements depends on several factors which are not present in open-circuit breathing apparatus or closed-circuit systems which maintain a constant PO_2 in the counterlung. The semi-closed circuit breathing apparatus (Morrison and Reimers, 1982) can be simply described as shown in Figure 1, with the gas mixture being supplied into the counterlung, oxygen and nitrogen being inhaled into the diver's lung through the carbon dioxide scrubber, nitrogen and unused oxygen being exhaled back to the counterlung, and with excess gas leaving the counterlung through a relief valve. Decompression calculations are influenced by the oxygen content in the counterlung which depends on the diver's work rate and consequently does not remain constant.

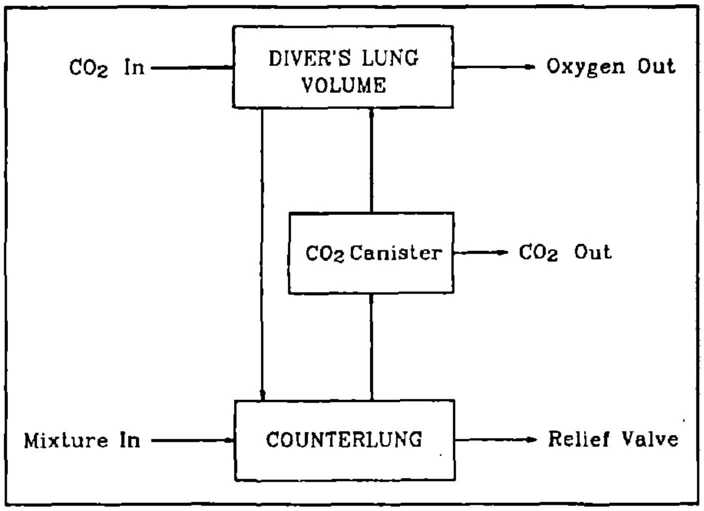

Figure 1. Simplified schematic of a semi-closed circuit breathing system.

The fraction of oxygen in the counterlung can be easily calculated by taking the amount of oxygen going into the counterlung minus the rate of oxygen consumed by the diver as shown in the following equation:

$$FO_2 = (FO_{2mix} * \text{Mixture flow} - O_2 \text{ used})/(\text{Mixture flow} - O_2 \text{ used}) \qquad (1)$$

where:

FO_2 is the fraction in the counterlung,
FO_{2mix} is the fraction in the supply,
Mixture flow is the flow rate in L/min, and
O_2 used is the diver's consumption in L/min.

The safe rate of flow for any mixture is based on having no less than a PO_2 of 0.2 in the counterlung at any time to prevent hypoxia. The O_2 content will be a minimum when the diver is working the hardest. Thus, either 3 or 2 L/min is used for the calculation.

The maximum safe depth on any mixture is based on a maximum of 2 bars of O_2 in the counterlung to prevent O_2 toxicity problems. The maximum O_2 content occurs when the diver is resting with a minimal O_2 consumption of 0.25 L/min.

$$\text{Depth} = (2 \text{ Bar} \times 10 \text{ msw}/FO_2 \text{ in counterlung}) - 10 \text{ msw} \qquad (2)$$

The EAD is calculated by determining the depth of an air dive required to achieve the same nitrogen partial pressure as the gas in the counterlung at the bottom depth.

$$EAD = (\%\ N_2 \text{ in counterlung} * \text{Depth (abs)})/(\%\ N_2 \text{ in air}) - 10 \text{ msw} \quad (3)$$

This EAD is then rounded up to the next depth in the standard air table to obtain the decompression schedule.

Table 3 shows the three nitrox mixtures, the safe flow rates, and the percentage O_2 in the counterlung for different steady state O_2 consumption rates (VO_2). The 3 L/min VO_2 is the maximum value that can be maintained with the first two gas mixtures and 2 L/min is the maximum for the third mixture. The 1.3 L/min is assumed to be the average consumption for a diver working for a period of 30 minutes or more (Royal Navy, 1987). The values of 1 L/min and 0.75 L/min are typical for descent to the bottom and ascent during decompression. The 0.25 L/min represents the resting diver. Thus, it can be seen that the percentage of oxygen can vary considerably in the counterlung.

Table 3. Calculated percent oxygen in counterlung.

Mixture O_2/%N_2	Flow Rate (L/min)	Percent O_2 for O_2 Consumption, in L/min 3.0	2.0	1.3	1.0	0.75	0.25
60/40	6	20	40*	49	52	54	58
40/60	12	20	28*	33	35	36	39
32.5/67.5	13	-	20	25*	27	28	31

* Values used to calculate EAD

Table 4 shows the EAD's calculated from the safe flow rates and the O_2 consumption rates shown. In practice, these EAD's are rounded up to the next depth in the Standard Air Table to gain additional safety.

For the 60/40 mixture, there is a 6 msw reduction from the actual depth (except at 12 msw or less). For the 40/60 mixture, the reduction in the EAD is 3 msw except at depths shallower than 24 msw where the rounded up depths would make them equal to the actual depths. The use of the EAD can result in big savings in decompression times and in some cases decompression stops can be eliminated completely. For the 32.5/67.5 mixture, the reduction in the EAD is minimal and it is common practice to use the actual depth schedules.

Table 4. Equivalent air depths.

Actual Depth (msw)	Equivalent Air Depths (msw) 60/40	40/60	32.5/67.5
12	7	11	11
18	11	16	17
24	16	21	23
30	-	27	28
36	-	32	34
42	-	38	40
48	-	-	46
54	-	-	51
% O_2	40	28	25
VO_2(L/min)	2	2	1.3

Table 5. Experimental O_2 levels from leaving surface to the end of the bottom time (B.T.).

Mixture $\%O_2/\%N_2$	Depth/B.T. (msw/min)	$PI.O_2$ Levels in ATA (% O_2)		
		Max.	Min.	Average
60/40	24/60	1.88 (55%)	1.42 (42%*)	1.60 (47%)
40/60	42/30	1.90 (36%)	1.45 (28%*)	1.64 (31%)
32.5/67.5	54/20	1.85 (29%)	1.40 (22%)	1.59 (25%*)

*Percentage O_2 closest to those used for EAD calculations

Table 5 shows an example of actual inspired PO_2 values obtained during the manned testing of the CCDA. The readings were taken with a mass spectrometer and are for the period from leaving the surface to the end of the bottom time. The PO_2 values are relatively similar for the three different mixtures. The results represent the average for about 6 divers working on a bicycle ergometer at 50 watts and 60 rpm.

The table also shows the percentage O_2 calculated from the PO_2 measurements based on the bottom depth. These values can be used to estimate the steady state VO_2 from Equation (1). The minimum values for the 60/40 and 40/60 mixtures represent an O_2 consumption of about 2 L/min and the average is slightly higher than 1.3 L/min. For the 32.5/67.5 mixture, the average would be equivalent to 1.3 L/min. Therefore, the VO_2 values used for calculating EAD are realistic when compared to these empirical results.

The question arises as to whether it would be beneficial to develop a set of tables based on the actual EAD values rather than on the EAD values rounded up to the next greater depth in the standard air tables.

Table 6. Calculated no-decompression times for 60% O_2/40% N_2.

Mixture $\%O_2/\%N_2$	Actual Depth (msw)	EAD	No-decompression times (min) for average VO_2 in L/min: 2.0	1.3	0.25
60/40	15	360	400		
	18	175	220		
	21	75	110	300	420
	24	50	65	190	250

Table 6 shows the no-decompression times for the 60/40 mixture. The values shown for the EAD (rounded up to the next depth) are taken from the DCIEM Standard Air Tables. (The DCIEM no-decompression limits are much more conservative than the US Navy limits.) No-decompression times for the exact EAD (i.e., without rounding up) are shown for 2 L/min and are longer. Thus a set of tables based on 2 L/min would allow longer no-decompression dives. However, it would be unlikely that a diver could average that high a level for such long periods. If a 1.3 L/min consumption is assumed, the no-decompression times become considerably longer and all dives with the 60/40 mixture, based on the CCDA endurance limit, could be done as no- decompression dives. However, dives will be limited by the CO_2 scrubber endurance, gas supply, hypothermia, and at the deeper depths, by too high a PO_2. (Note that the calculated no-decompression times for the different O_2 consumption rates are theoretical only, and have not been verified experimentally).

Table 7 shows the calculated no-decompression times for the 40/60 gas mixture. For depths shallower than 24 msw, there is a large difference between the EAD no-decompression times and the 2 L/min value because the EAD values are rounded up to the actual depth. Here the 2 L/min times are more beneficial. However, there is no advantage in using this mixture for these depths when compared to the times allowed for the 60/40 mixture. For depths from 24 to 36 msw, the EAD and 2 L/min values are the same. Assuming a lower O_2 consumption rate would increase the no-decompression times. However, for the shorter bottom times at the deeper depths, it is possible for the diver to maintain a higher rate of work and it may be better to calculate decompression schedules based on 2 L/min. Therefore, it is not obvious whether a separate no-decompression limit for this mixture would be valuable. Only manned experiments would answer this question.

Table 7. Calculated no-decompression times for 40% O_2/60% N_2.

Mixture %O_2/%N_2	Actual Depth (msw)	No-decompression times (min) for average VO_2 in L/min			
		EAD	2.0	1.3	0.25
40/60	12	175	290	440	
	15	75	125	220	350
	18	50	70	100	200
	21	35	50	60	90
	24	35	35	45	60
	27	25	25	35	50
	30	20	20	25	30
	33	15	15	20	25
	36	12	12	16	22
	39	10	11	12	20
	42	8	10	11	15

For dives requiring decompression, calculating decompression schedules based on 2 L/min for the 60/40 and 40/60 mixtures and on 1.3 L/min for the 32.5/67.5 mixture will offer some advantage over using the EAD in most cases. In addition to the round up factor, there is also another consideration that tends to make the EAD schedule more conservative. The stop times on the EAD schedule are based on 21% O_2 whereas the actual percentage of oxygen with the breathing apparatus will be higher, particularly since the diver will not be working hard during decompression. Thus the stop times during decompression can be reduced because of the higher oxygen content in the counterlung. Specialized tables could be also developed, for example, by assuming 2 L/min for the bottom period and some lesser rate of O_2 consumption such as 0.75 L/min for the decompression phase.

As an example of how the decompression times can be reduced, Table 8 shows decompression times calculated from the experimentally observed PO_2 values shown in Table 5. Decompression times have been calculated from the DCIEM air model based on the EAD, the minimum PO_2, and the average PO_2 value. It can be seen that the decompression times could be reduced considerably, thus allowing longer bottom times, if calculations were based on similar experimental results.

The calculations shown here are theoretical and the decompression times have never been tested. However, these calculations do show that a study of the decompression requirements is warranted and that it would be advantageous to use specific tables for semi-closed breathing

Table 8. Calculated decompression times based on experimentally observed oxygen levels.

Mixture $\%O_2/\%N_2$	Actual Depth (msw)	EAD (msw)	Bottom Time (min)	Decompression Times (min) EAD	Min. P_IO_2	Avg. P_IO_2
60/40	24	18	90	16	0	0
40/60	42	39	50	82	66	55
32.5/67.5	54	54	20	45	43	36

systems rather than using EAD's and Standard Air Tables. The advantages of such tables would be the reduction in decompression times and the increased no-decompression capability. The disadvantage of such tables would be the amount of testing required to verify the validity of these tables. The EAD has an advantage in that the decompression is conservative and thus should be safer. Also, it means that only one set of tables, the standard air table, is necessary for air dives or nitrox dives.

SUMMARY

A study of the decompression requirements for semi-closed breathing apparatus such as the CCDA, in which the oxygen content in the counterlung varies with the diver's work rate, has shown that the traditional method of decompression using the EAD and the Standard Air Tables is conservative and should be safe. However, specific decompression tables based on the actual O_2 consumption rates can be beneficial by increasing the no-decompression limits and reducing decompression times. In the future, if alternative gas supply systems such as umbilical support, which is a feature of the CCDA and CUMA, are used, new possibilities for optimizing decompression schedules and bottom times become available, for example, O_2 decompression or surface decompression with oxygen. In any case, research in the form of mathematical modelling and human experimental diving will be required to establish the advantages and safety of the new decompression tables and to determine the restrictions on extending the dive time due to hypothermia, CO_2 scrubber endurance and high PO_2.

DCIEM No. 88-TR-07

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<u>Discussion following Mr. Nishi:</u>

CAPT HARVEY: Ron, when you all train your people for these rigs, how much training goes into it? How many days or weeks go into training them to be competent?

MR. NISHI: Most of the Canadian Forces' divers are already trained, and it is estimated that very little, a matter of hours, is required to get them up to speed on this part of it. The time is supposed to be a fraction of the time required to learn diving in the first place. I cannot tell you in terms of hours.

CAPT. HARVEY: With our Mark 6 rig, when I trained with it in 1969, it was a three week course to learn to set it up and dive it and operate it. I would be interested in what the training time is for other semi-closed and closed-circuit rigs.

MR. NISHI: I cannot find it in here at the moment, but it is estimated that the time is very small compared to training for a normal semi-closed-circuit system.

One other the things you have to realize is that requirements for military diving are quite different than for civilian purposes. We can tolerate going closer to a decompression limit than possibly other people, say commercial people.

DR. HAMILTON: You mentioned that the limit was sometimes thermal. From the picture these fellows are wearing wet suits. Why not dry suits?

MR. NISHI: Yes. Well, for the present application I guess that is what we have in the system, but we are doing an evaluation right now of different dry suits for Canadian divers. Whether they will be switched for this application, I do not know.

Chapter IV. Diving activity summaries and final discussion

This chapter, in addition to the final discussion, contains short presentations by several participants, including individual perspectives and some cogent reports of enriched air nitrox diving activities.

Discussion by Mr. Dick Rutkowski:

Mr. Rutkowski after a navy diving career became the leading trainer of NOAA divers and diving doctors in both special diving techniques and decompression chamber operation. He currently offers training in the NOAA Nitrox I method.

MR. RUTKOWSKI: Generally, it seems that a lot of the information for this Workshop is coming from agencies like universities or government.

I think a lot of you people know my background. In 1985 I retired from the government as Deputy NOAA Diving Coordinator working for Morgan Wells, and the Director of NOAA Diving Training. From 1965 and on I began to conduct all of the
e diving training for NOAA. I was also the director of the hyperbaric facility in Miami, which was probably the most active diver treatment facility in the country. So from a hyperbaric facility, and from the operational diving aspects from the early 1970's we began to realize the need for the use of this nitrox mix and we began to start to teach it.

We conducted many courses in nitrox in different parts of the country. So must of the use of nitrox today probably branched off as a result of Morgan Wells' work with NOAA and some of the things I had done.

The second area where we began to use nitrox in about the mid seventies was for therapy purposes, so that once we went deeper than 60 fsw pressure in a decompression chamber, we could get the hydrostatic effect of pressure plus we would be able to get the effect of oxygen similar to what it was at sixty feet.

But the best advantage of using the therapy gas mix when doing decompression treatment is for the attendant, mainly the physician who wants to lock in with a critically ill patient and wants to get out as soon as possible. A physician does not want to be trapped in a decompression chamber.

So we started using nitrox there. The physician locks in and breathing 40% oxygen goes to 165 fsw and his EAD is 117 fsw. Instead of having 5 minutes no-d and being at a 165 fsw narcosis level, he has 10 to 20 minutes--the no-decompression limit at 120 fsw, the EAD--and he is at the 120 fsw narcosis level, too. So he has a better ability to work with his patients, and to get in and get out. [EDITOR'S NOTE: Some narcosis experts believe that oxygen is at least as narcotic as nitrogen.]

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So with every course that I teach for decompression therapy we teach the EAD concept. Some of the people in the room here have been through my training programs, so they know and understand the EAD concept and have used it for years.

Now that I am out of the government I am in the training business. I conduct hyperbaric training programs to teach people how to run decompression chambers and how to treat divers. My programs are very heavy in the area of life support systems and gas, including if you get into saturation treatment and things like that.

But I presently now have two hyperbaric facilities of my own. I have one in the Turks and Caicos Islands and one in Key Largo, Florida. We primarily have used these places for education. At the one in the Turks and Caicos Islands physicians can come and get their CME credits and still have fun in the sun. In Key Largo people come to get an intensive 8 or 10 hour 1-day program on the use of decompression chambers.

But now that I am independent I am beginning to see more of what the sport diver is doing. I am getting more away from the professional diver. What I began to see is that some of the things that some of these people are doing are really ludicrous. We know the sport diver probably knows a little bit about oxygen and oxygen toxicity. So these guys, of course, are pushing air much deeper than the safe physiological limits for air. We know the safe physiological limit for narcosis is 130 fsw, but when you go to 218 fsw, then you are pushing over 1.6 atm of PO_2 and it is oxygen that you have to be concerned with.

So some of the things that I am seeing now is that sport divers are going deep and pushing 1.7 to 1.8 atm of PO_2 with air and then they are coming up to 30 fsw right away and going on oxygen at 30 fsw. If you go on oxygen at 30 fsw you are going from 1.7 and following this with 1.9 atm. Your oxygen clock is running. We have had two cases of convulsions, people that were brought in to us as a result of convulsing at 30 fsw and not on the bottom.

So this is one area where I see divers are starting to misuse oxygen drastically.

Now, the other thing I have begun to see was at the DEMA show the other day, the Diving Equipment Manufacturer's show. I threw my (nitrox training) literature on the table. People would come by and a lot of them would say, "What is this? I never heard of it. Boy, can you go deeper with this than with air?" Other people would come by and say, "We know all about nitrox. My husband is a commercial diver and we use nitrox all the time."

I asked, "How do you use it? What do you do?" "Well, it is easy. You just put a little bit more oxygen into the cylinder. When you put a little bit more oxygen in the cylinder, there is less nitrogen, and if there is less nitrogen, that means you can go deeper and stay longer." So this is what they believed nitrox was. That was one instance.

In another instance a guy came by and said, "Oh, yeah, I use it all of the time. I put in 15% more oxygen in my tank, and by putting 15% more oxygen, I go to the next higher stop and it gives me a little extra bottom time. Well, that one is not too bad. Supposedly he drains his tank each time and he analyzes the gas each time and hopefully he does not put oxygen on top of oxygen so the PO_2 begins to accumulate and becomes higher and higher.

So these are the kinds of things that are going on out there. So what I have decided to do at our facility in Key Largo is set up a training program. Of course, my facility is already a training facility for the medical people, the chambers, but my main intent now is to bring in people like yourselves who want to have training in nitrox, and to provide that type of training. This is what I am doing.

I have been working some with the Coast Guard and NASA and different government agencies, Army special forces, and things like that. So this was my primary reason of putting in a nitrox installation. I have three high pressure air flasks and can actually have on hand about 10,000 cubic feet of gas at any time. I can mix by partial pressure or use Morgan's method to mix by blending.

Another thing that has happened is that the Department of the Interior, NOAA and so forth, have dumped two old Coast Guard cutters offshore outside of the Key Largo sanctuary. They are 13 miles off shore sitting on a nice sandy bottom. One of them is upright. They were purposely set up so that they would be a diving facility to try to take pressure off of the reefs, to get some of the divers off of the reefs because they are really tearing up the reefs.

Beautiful dives. Right to the bottom is about 175 feet on both of these cutters. All of the hatches are off. All of the ports are off. You can swim in and you can not easily get entangled, at least not yet until the fishermen get their nets in there and the nets get all over it, but that is another problem for the future.

So these sport divers are diving down on them. At 130 fsw you have a 10 minute no-d.

So I said I am going to try to get things organized, and I got together with some of the dive shops. What I am planning on doing now is to set up a one-day nitrox training program which is only going to teach the use of NOAA Nitrox I, not the EAD concept. It is in my brochure. That is for the more advanced group. Teach them NOAA Nitrox I.

When these people come through the course, they are given all of the lectures in oxygen toxicity and so on, and they are given a final examination that they have to pass, and they are given a certification card. We provide them a guide to go out to the wreck. We try to keep them up on the upper deck, which is about 90 feet. We try to explain the dangers of going deeper and so on.

On the boat are people that are using air, and there are people that go from my class that are using nitrox. So what we show them then is exactly what we teach. The tanks have to be color coded, the tanks have to be marked. Each sports diver that goes through the course has to be at an advanced diver level. He must show a log book of having done previous dives of that nature, wreck diving and diving to those depths, and diving in that environment. It is not just a matter of Rutkowski going crazy and taking all of these people out. It is a matter of trying to train people, trying to at least get a few people to go through the program so that they can pass on to all the other divers about the misuse of oxygen, and that they can actually use the nitrox.

We do not teach them how to mix. We teach them the dangers of the use of oxygen, oxygen handling, oxygen safety, what not to do, and so on. So hopefully some of this information will get passed off to the general sports scuba community and maybe by doing something like that we can help to put more safety out into the field, as more and more divers become aware of oxygen toxicity, the misuse of oxygen, and so on.

Today I have about 30 divers at the advanced level taking the program. These guys, if they clean a tank according to our specifications, color code it according to our specifications, and if they present my certification card to our dive shop, they will be entitled to get a nitrox fill for $6.00.

Another individual and I handle all of the mixing. We mix it and we analyze it. We let it stand. We analyze it some more.

When the diver gets a tank of gas, he has to log in the log book the tank serial number, the percentage of oxygen, and so on. The diver does the final analyzing which is the only correct thing to do in any type of oxygen-enriched gas diving or mixed gas diving. So I think it is going to be something that is going to work and will add safety.

R. STANTON: Do you have any support from the sport training agencies for this kind of program?

MR. RUTKOWSKI: No. Do I need it?

MR. STANTON: No, but I was curious.

MR. NORRIS: Do you require O_2 clean first and second stages?

MR. RUTKOWSKI: Over the years we have gotten away from that, even in NOAA. Initially we used to do it but, no, we do not.

MR. NORRIS: So divers do not need a dedicated regulator?

MR. RUTKOWSKI: No. Again, I know some people disagree with me, but the Compressed Gas Association book does say 40%. Still we would recommend that these things be oxygen cleaned, yes. The better you can clean these systems, the better off you are going to be. [EDITOR'S NOTE: See notes on pages 27 and 48.]

DR. VANN: 40% for high pressure oxygen or low pressure?

MR. RUTKOWSKI: High pressure.

DR. WELLS: Some people have had to use enriched air for such things as SCBA's going inside of nuclear reactors, and that is when I started getting interested in it. So they are now using up to 40% for high pressure oxygen-rich mixtures in systems that are not cleaned for oxygen service. Now, if you are mixing in the cylinder, that does not apply because you put pure O_2 through it, but in a system that sees only the gas in question it is okay.

MR. RUTKOWSKI: So the nitrox concept goes all the way both to the Navy in 1962 using the Mark 6 system, up to when NOAA published this concept in the NOAA Diving Manual in 1979; it has been in there for ten years. Who are the biggest purchasers of the NOAA Diving Manual? The sports scuba community.

Nitrox has been around for many years. It is a safe gas. I only know of one case of an individual that was bent using the gas and that was because of his own stupidity. So I am looking forward to working with it.

If I can help any of you people in the future, I will be glad to do it. I have a total system like Morgan showed you. I can train in any facility and provide training with the blending method or partial pressure method.

DR. HAMILTON: Would you tell us a little bit more about those two cases, when people got hits while decompressing at 30 fsw on oxygen? Had they been on dives with higher than normal exposure to oxygen before that?

MR. RUTKOWSKI: No, they were diving at around 240 fsw which gives about 1.7 or so ATA's of O_2 at that depth.

DR. HAMILTON: Were they there very long?

MR. RUTKOWSKI: On the bottom they were down about 20 minutes, and then they would come right up to 30 fsw and at 30 fsw they would go on the pure O_2. You would think that the time break between the bottom while they are sliding up for a couple of minutes would have possibly eased the oxygen toxicity.

MR. GALERNE: They go from 240 to 30 fsw without stopping?

MR. RUTKOWSKI: Right. When they get to 30 fsw, they have a tank of oxygen hanging there and they start breathing off O_2 and, of course, the currents are there and they are kicking.

DR. HAMILTON: So they are not at full rest?

MR. RUTKOWSKI: Oh, no, they are hanging on a line kicking, swimming.

DR. HAMILTON: How long after they get to 30 feet and go on oxygen ...?

MR. RUTKOWSKI: I think it is about ten minutes if I recall. I would have to go back and look.

DR. HAMILTON: Were these full convulsion?

MR. RUTKOWSKI: Yes. One day one guy was seizing and the four other people had to go down and get him and we wound up with about four people needing to be treated because they had to get the guy that was seizing and sinking.

DR. HAMILTON: After the first guy had a convulsion, did they continue using the same technique?

MR. RUTKOWSKI: I think some of you people know the person involved and he was one of these deep divers, wreck divers, and since then his certification has been taken away by the national certification organization.

DR. HAMILTON: This is a practice that is considered acceptable in some places, oxygen at 30 feet?

MR. RUTKOWSKI: Exactly, a lot of people use it, but you have to remember your oxygen toxicity clock is always running.

CAPT. HARVEY: Speaking of in-water oxygen, the Australians for treatment of DCS in isolated areas have popped up with this 30 foot whip which delivers pure O_2. Does anyone have any information on what their experience has been with hits occurring at the end of the whip at 30 feet?

DR. CROSSON: I think we have to kind of stick with the issue of nitrox with sport diving.

MR. PARKER: You said that you will fill their individual cylinders if they are clean and have the label?

MR. RUTKOWSKI: Right, and they have a certification.

MR. PARKER: I am just a little concerned with that, having seen the disrepair of a lot of the equipment of people in the sports community. It would seem it would be to your advantage to rent them a full rig that you maintain control over.

MR. RUTKOWSKI: I do that, too. But like I say, the equipment comes under my visual inspection.

MR. PARKER: You actually go through and inspect all of the equipment?

MR. RUTKOWSKI: Yes.

MR. GALERNE: How much insurance do you carry?

MR. RUTKOWSKI: Insurance, none.

MR. GALERNE: Oh, good.

MR. RUTKOWSKI: I do not believe in insurance.

MR. PARKER: Not worth suing.

MR. RUTKOWSKI: I do not believe in it. That is why I have a facility in the Turks and Caicos Islands.

DR. CROSSON: If I could, this is important for the record just to verify that this Workshop is not to support or have an opinion on sport diving, although we just had a presentation on it.

Discussion by Mr. Jack Nichols:

Mr. Nichols is diving officer at the University of Miami, a school with an active diver-oriented oceanology program, and he has introduced and used nitrox techniques in that setting.

MR. NICHOLS: The University of Miami have only been involved with nitrox for a year or so. We have not had too many projects. Most of the diving at the University is in shallow water, 20 feet or so, so air has been just fine. But we did have a project in Key Largo where we were able to use 68/32 N_2/O_2 and double our no decompression times. We think there was a total of about 15 dives made and we did stick with just the one gas, 68/32, basically Nitrox I. That is the only project we have had until now other than training dives. We have used other mixtures on training dives to get our people familiar with it.

We do have one project coming up in May down in the Bahamas where we will be using nitrox. It is in about 90 feet of water and we will probably be using 63/37 N_2-O_2 on that one.

We hope to get more use in the future; now that our people know it is available I am sure it will pick up.

DR. CROSSON: Did you have difficulty convincing the Diving Control Board, or are they pretty open?

MR. NICHOLS: No, not really. We went through Morgan's course at NOAA, and presented it to the dive committee and they thought it was a great idea; it was no problem at all convincing them to accept it.

DR. CROSSON: The scientists were pretty open?

MR. NICHOLS: Yes.

MR. NORRIS: Do you do your own mixing?

MR. NICHOLS: Yes.

MR. NORRIS: Do you have dedicated tanks and regulators?

MR. NICHOLS: Not regulators, but tanks. We use a label. I did not bring one with me but we had a label made up. I will send one to you. We have a label to stick on the tank that does say it is nitrox, it is not air, just in case somebody were to pick it up. That should not happen because I am the only one with a key to the room. If by rare circumstances somebody got hold of the tank, it would be labeled that it is not air and what the mixture is and who mixed it and that sort of thing. So we do have real good control on the cylinder.

DR. CROSSON: Just from a personal perspective of having been down there a couple of times, there is a lot of control. I was real pleased with the labeling and whatnot.

Discussion by Mr. Terry Overland:

Mr. Overland is Safety Officer for Oceaneering International in Morgan City, LA. His company has used enriched air diving techniques in commercial operations for 6 years.

MR. OVERLAND: Oceaneering has about 32 offices around the world, in 17 different countries. We employ approximately 1500 to 1800 people who are all dedicated to diving.

We started using nitrox equivalent air depths in approximately 1982 and 1983. It came about in the North Sea, trying to get the extended bottom times. It is not scuba, ours is all surface supplied. We mix it on site to the diver with the blender. It is called the Polychrome 101 made by Dräger. The system costs about $15,000. The unit is electrical, and has electrical power supply to run its analyzer system and visual alarms. We supply pure O_2 to the system, and we supply air from an air bank with a backup HP air compressor. For safety, when we get an alarm we switch over to air, in case of the pressure dropping or the O_2 changing from what we have set for. We will switch over to either the air or a backup nitrox premixed bank.

For simplicity we have set our O_2 limits using the 60/40 and the 68/32 O_2-N_2 mixtures. That is simply because that is what the Polychrome 101 mixes--one into the other--and that sets limits on them with the 60/40 of 100 feet, and 130 feet.

To date now we have made approximately 7000 dives using this. Most of them have been well over the no-d limits, closer to optimum bottom times according to the Navy tables.

We use them at approximately 70 to 100 fsw so some of them have been Sur-D O_2 dives with decompression tables. To date we have had no decompression incidents and no o_2 problems using it.

CAPT. HARVEY: Is that Sur-D O_2?

MR. OVERLAND: Sur-D O_2. We rarely use the Sur-D air tables.

DR. WELLS: The mixers both you and Andre are using, are they the same ones you formerly used for heliox?

MR. OVERLAND: The Polychrome 101 is more for nitrox mixing. It is used for fire departments and for going into smoked filled rooms and so forth. It is 600 p.s.i. output, so you cannot use it to fill scuba cylinders.

I would imagine we dive approximately between 25,000 to 30,000 dives a year. Of that we make probably 200 scuba dives. So ours is all surface supplied.

DR. WELLS: But aren't these commercial mixmakers that are used for heliox perfectly adequate for doing the nitrox?

MR. OVERLAND: Yes.

MR. GALERNE: You have it on line and you use what you want, helium or oxygen or whatever.

MR. OVERLAND: There are three or four commercial mixmaker units available, such as the McDermott blender--well, McDermott is not blending them anymore.

Air Projects makes one and Gas and Equipment makes one. You are talking some $15,000 or $20,000 for a unit.

DR. WELLS: They are all low pressure?

MR. OVERLAND: It is 600 p.s.i. output, and you put a booster pump on the end if you want to charge cylinders.

MR. RUTKOWSKI: You said the low end of your oxygen input was 32%, so you have to use the pure gas compounds?

MR. OVERLAND: We use pure O_2 in the high pressure end. The Polychrome is made to take pure oxygen.

MR. RUTKOWSKI: I understood that the range of oxygen input into it may change, the low end was 32% and the high end was 40%?

MR. OVERLAND: That is the output of the machine. It is a blender. It just takes O_2 and air and blends it within the machine. It has analyzing equipment that controls all of the valves and analyzes what is coming out, and there is an alarm system.

MR. REED: How many dives did you have with it?

MR. OVERLAND: About 7,000. Very little has been done in the United States.

On one job in particular we started out and had a couple of bends and switched over to this; we then did 700 dives in the 70-80 fsw range with absolutely no problems at all. We have two of these systems in operation right now, the Polychrome mixers.

MR. DINSMORE: You say you used basically two different mixes or do you use the broad spectrum?

MR. OVERLAND: We have limited it to the 32% and the 40% as our O_2 parameters. Our limit is 1.6 atm PO_2 on the bottom, so that limits the two mixes to 100 fsw and 132 fsw.

MR. DINSMORE: Do you have a set of tables for these?

MR. OVERLAND: No, we just shift right over to the USN tables. Our Sur-D O_2 tables are slightly different.

CAPT. HARVEY: Are your supervisors putting any fudge factors in? Are they skipping a table or doing anything else to make the thing safer?

MR. OVERLAND: We do abide by the 2 + 2 rule; within two feet or two minutes of the end of the table we will jump a table. Also with hot water heating we found an increase in bends. So if we are using hot water, we will almost automatically jump a table; in the North Sea that is standard practice using hot water.

DR. CROSSON: You are talking about 1.6 atm PO_2; is that commonly what you use?

MR. OVERLAND: 1.6 is our limit for bottom mixes for the extend of our tables, no matter what table. We do have almost the same limits that have been shown up here as far as going with the higher pressure.

DR. CROSSON: I am just thinking about on bottom?

MR. OVERLAND: It is basically 1.6 atm. We do have tables that go up to 2 ata PO_2; we are limited to 30 minutes of bottom time on those, which I think basically is what the Navy has been saying.

Discussion by Mr. Paul Heinmiller:

It is clear that dive computers are part of the immediate future for scientific as well as sport diving. Mr. Heinmiller is an engineer at Orca Industries, manufacturer of the most widely used dive computers in the U.S.

MR. HEINMILLER: Orca Industries is the only U.S. based designer, developer, manufacturer and distributor of dive computers. That is all we do. We have competition in the United States but none of them do all of the aspects of the computer as we do it. We are responsible for what we do from beginning to end. We sell them to the dive stores. Most of our users are sport divers. The more conservative aspects of the industry, the scientific group, the military and commercial, have made other arrangements, but computers are coming and it is just a matter of time. We are not concerned about the conservatism. We think it is a safe and smart idea to be conservative.

A little bit of terminology. We do not build "decom-meters" and we do not build "decompression computers." We build dive computers. There is a big difference between those three things. That is just so we keep things straight.

We have two current products. The Edge is our oldest computer. It came out in 1983. We have just built the 10,000th Edge, and all 10,000 are still, as far as we know, active in the field.

A conservative estimate of the number of dives as of the first of this year is 600,000 dives. That is based on an estimate by Edge users that they make an average of 86 dives a year on the Edge, which maybe a little bit extreme. That 600,000 is based on 50 dives a year rather than 86. So we figure that is a conservative number.

With the success of the Edge we decided to fix some of the other aspects of the device so in 1987 we came out with the SkinnyDipper, which is aimed at more of the recreational diving population. It is not as rugged and not as expensive and a little less full function than the Edge, but it runs the same exact algorithms as the Edge does.

We have some other products in development in terms of dive computers, some of which are "ultimate" dive computers. Some very interesting functions are being conceived to go into them. One of the possibilities for the full function ultimate computer, after what I listened to here, seems to be the possibilities to do EAD nitrox work. Otherwise it is possible in current technology to put an EAD nitrox model for a specific mix like Nitrox I or II into a specific computer marketed for just that, but for the highly variable mixes of the EAD complex we will have to wait for a smarter computer like we are working on right now.

One of the things I heard here is the need for data loggers to help with decompression model research. We are very interested in supporting decompression research, especially in the areas which Edge users and SkinnyDipper users are working in. Those are areas which largely have been ignored because it is so complex. We would like to investigate repetitive, multi-level, multi-day, and no-stop or short-stop decompression diving.

Single dives are interesting, but you do not buy an Edge if you are going to make one dive a week. It just does not pay off.

There are a couple of points that I want to make about decompression "model" based computers, which is what we build. We do not build table readers. A lot of the safety factors inherent in the use of tables that are not in the tables themselves but in the way they are used are not found in a dive computer.

The fact that when you are diving at 51 fsw and use a 60 fsw table adds conservatism that you do not get with a computer, because a computer dives you at 51 fsw. There is no J factor built into the computer; it runs the model directly. So we have to put a conservative model into the computer.

The most important aspect is user training, letting the users know that we feel the model is reasonable but if they want to add conservatism, they need to do it themselves. The computer does not know you are cold and shivering and the computer does not know you are ten pounds overweight or other predisposing factors.

That is the main thing. We do not want people strapping the computer on their arm and figuring that this thing takes care of the whole spectrum of decompression. We want to keep intelligent users out there. And anything we can do to help the scientific community and the research community we would be happy to work on.

MR. OVERLAND: Have you had any feedback from anybody having decompression problems with using the Edge?

MR. HEINMILLER: Yes. They are going to present a paper this summer looking at 38 cases now. Two months ago it was 37.

UNIDENTIFIED PERSON: Strictly from the Edge, or all diving computers?

DR. VANN: All diving computers. Primarily the Edge, because that is manufactured in this country. Our abstract [Appendix to Vann paper] describes our initial analysis.

MR. HEINMILLER: His data shows that most of the bends are in the multi-level, multi-day category, but then that is where our computer users are diving.

DR. VANN: They tend to be in decompression diving, and there is an indication that an individual's susceptibility is an important factor, too.

MR. HEINMILLER: Right. We see that a lot. We pass everything we learn into Dan. In talking with people we get cases of 6 people diving the same profiles and one person gets bent, this sort of thing. Many of those 37 are that way.

MR. OVERLAND: You say it has a data logging feature. Can you read back the dive profile?

MR. HEINMILLER: No, not with the Edge. The ultimate computer we are working on will have a full data logger. In the meantime we were asked a couple of weeks ago to build special data loggers for Dudley and some stuff he is doing with Disney World. I suspect we can do that relatively quickly, so that you can have a special purpose data logger that you can put on a diver which has no decompression function at all but merely samples and stores and reports back time and depth.

MR. OVERLAND: If you come up with something like that, I would like to get some information.

MR. HEINMILLER: I think we are going to do it. Almost everybody we have talked to has mentioned a need for that. I really liked the Suunto picture of what the guy remembered and what the computer said. We are going to do something like that, probably in Edge's case because that cuts costs.

MR. NORRIS: Can you envision being able to scale it down?

MR. HEINMILLER: The Skinny-Dipper already is. The next generation of Edge will be a little smaller but it will also be connected to the tank. High pressure to it will not be just a tack on device. It will be about the size of current consoles so its size will not be a problem on the new device.

CAPT. HARVEY: One of our biggest problems in the U.S. Navy and particularly with the Weathersby approach to doing analysis and what have you is the lack of adequate data on what has been done. People do not dive the tables as they are written and they do not often record exactly what they did dive.

One of the advantages of a dive recorder like this is that you can keep track of what your people actually have done, and that enables you then to feed it back in and make improvements in your system. But if you do not start by collecting adequate data, you will never get there. So this approach offers a rational approach to getting some data that you can use.

MR. HEINMILLER: The real benefit is that now either by a data logger running a model dive or putting the model in the computer itself you can actually dive the model itself rather than the table. So you are pointing out problems in the model itself and not problems in the table manifestation, and that could bring some real interesting answers for everybody.

MR. GALERNE: As a comment on that, IUC does not do scuba diving; we do surface air supply. For years now we have recorded diver profiles on a mechanical time-pressure recorder.

For example, when divers close the door of the bell, they pressurize themselves to make the seal before we move them out. You would be surprised how much the bell goes up in pressure at that point. That is a factor affecting the decompression table. We have been about to redefine it because of this. My people are very concerned about that.

DR. DAUGHERTY: I agree. I have never understood why time-depth recorders have not been used for a long time. In Brian Hill's book he talks about the Okinawan pearl divers off the coast of Australia, where they hooked those things on to see what their dives were. In evaluating dive accidents and looking at the dive log, imagine that the man keeping the record is a 20 year old tender with grease on his hands and everything. You can see places where he erased it, because what he was doing was keeping time as best he could. He has one hand on the valve, one eye on the diver, and he tries to keep the log. When he gets to the bottom of the form his dive does not add up. He has 37 minutes there and only 36 minutes adding up the steps. So he goes back and erases one and makes it right; that is just human nature. That does not make him a dishonest person. It just means in his mind his supervisor is going to be very angry with him if he does not have every letter perfect, knowing that a doctor or an insurance person is going to analyze those records. All he wants to do is go home and sleep at night. That is the dive that supposedly actually occurred.

Like you say, when you show that Suunto data, you just know that is right. You just know that people do not remember exactly what happened, and then when they start writing it down they are going to make it look right. So you have a memory and then make a record that polishes up the memory, and that is what goes down as the facts that actually happened. That is how you can analyze decompression sickness.

MR. GALERNE: In the diving industry there is another problem. It has had recorders for 20 years; those are regular pen recorders, you know, you buy them for 500 bucks. One of the objections of recording, funny enough, is that a lot of my colleagues were objecting to recording because in case of an accident, you are stuck. If it is recorded on paper, then you are hurting.

DR. DAUGHERTY: Right. If you do not know, you may stay out of trouble; however, if you do not know you also have no chance of correcting the problem and making your work safer.

MR. GALERNE: This recording is invaluable, but the problem, as I said, is that the industry is not ready for the recording because of the insurance problem.

DR. DAUGHERTY: And a step beyond that, the litigation problem. It is fair to say that people generally have their own best interest at heart and then they get scared out of something that is rational and sensible because of the fear of an attorney, a rapacious lawyer, that might make them look stupid or cost them a lot of money.

MR. GALERNE: I believe deeply myself that if one of my people makes a mistake, I have to pay for it. That is it.

DR. DAUGHERTY: It is easy to understand how this came about. My feeling is that the way to eliminate mistakes is to get facts.

MR. GALERNE: Also, the fear of being found wrong makes people more cautious. For the person that has the recording equipment knows he better watch out, because if he makes a mistake, you know about it.

MR. STANTON: At a recent conference in Malta the scientific committee came to a consensus that the reason why they felt that dive computers had not become accepted at the various agencies was for a lack of a data recorder or a profile recorder. That is part of their final report.

MR. HEINMILLER: They were putting that into future computers but previous ones have not been smart enough to do that.

Discussion by Mr. Greg Stanton:

Mr. Stanton is Diving Officer at Florida State University, which has an active diving program and some upcoming projects for which special breathing mixtures are likely to be helpful.

MR. STANTON: I am particularly pleased to be invited to this Workshop. It comes at a timely period in our program's development.

We are at a typical university of about 25,000 students and support anywhere from 50 to 100 diving scientists at any one time, working in a variety of areas. This is typical of many of the other universities represented here.

As a diving officer at the University, I have to face diving control boards and a lot of internal politics to bring about the introduction of nitrox and other exotic diving activities. We can not just pull an O_2 bottle out and fill a cylinder and jump in the water. We have to provide standards for the use of this equipment and training of its participants. We have to provide a full facility, and, of course, maintain it to certain standards. We have to provide training for its safe use and supervision out in the field.

We have to provide support equipment, dedicated cylinders and whatever else is required, and, of course, we have to have some kind of justification or a good cost-benefit ratio.

Last night Les Parker from the University of Florida and I sat down over some figures trying to figure out just what this is going to cost, and we came up with a value of about $20,000 to bring nitrox on line over the air systems that already exist. Now, that is making some radical assumptions, for example, that we will have to buy a new compressor. Florida State is already doing this.

We also predict--at least at FSU--about 500 dives the first year on nitrox. Obviously later years will bring the costs down.

When you divide that out, it is very straightforward. The first year we predict it will cost us about $40 a dive over what it would have cost to make the equivalent in air dives to comparable depths. That is assuming that we do not take this any further, without things some agencies have required such as O_2 tolerance tests, on-site chambers, and so forth. This is the bare minimum of how we can get by as cheaply as possible. We are patterning our system after Morgan's, rather than a commercial mixing system.

We predict in the next year to be using the nitrox on at least two different projects, one in relatively shallow water and one a little bit deeper. I wanted to bring up that bit of information.

The other area we are launching within the next six months is an ambitious program at Warm Mineral Springs, which will involve deeper diving to 170 feet with a component in the 60 to 70 foot range intermixed with the deeper diving activities. We have been talking to a lot of people about mixed gas diving and nitrox diving, and obviously both will find a place at this site.

This site has been worked now for a good 10 or 12 years, not under the university but under the Department of State using inwater oxygen decompression at 30 feet, and so forth. So there may be a very good data base to jump from.

We also have proposed another project coming up in the Gulf of Mexico in around 120 to 150 feet. So again we see a trend at the University of moving into the deeper depths and into the more exotic gases, and not necessarily diminishing the shallow and more traditional scuba activities which I am sure will continue on.

MR. REED: Are you doing these dives to 150 and 180 fsw without a decompression chamber?

MR. STANTON: No, we have a chamber at the site.

By the way, Florida State University inherited this Warm Mineral Springs project in July of last year. We stopped all diving at that time, and we have gone through a review process; we will resume when we have them backed up and on line. We expect to use mixed gas with the proper support facilities and the proper supervision for the project, which we hope the industry will feel is proper.

As far as the other work in the Gulf of Mexico, yes, we hope to have a chamber on board a vessel to do that kind of work.

MR. DINSMORE: Have you decided what you are going to use in the way of gas mixtures?

MR. STANTON: At the springs, no. There are two or three different ideas that have been kicked around; one of them was to go to the heliox, another one was a tri-mix.

The obvious choice of the PI is for straight air and we are very inclined not to, although there is a body of knowledge to suggest that that might be appropriate. Those are the three right now.

In the shallow areas we are talking about nitrox. That is why this Workshop was very timely.

Discussion by Mr. Michael A. Lang:

Mr. Lang, San Diego State University, is President of the American Academy of Underwater Sciences. This organization represents the scientific divers, who are the primary recipients of the technology discussed at this Workshop.

MR. LANG: First I want to say that I think the nitrox diving standards have been approved by the Academy. There were submitted and reviewed by Dudley, so they are available and will be appended in the next printing of our Standard for Scientific Diving Certification.

I think in light of some of the information that has come out here, we will be able to look at that again and add a few points here and there.

Any new tools that come along for us scientists in diving, the dive computers, nitrox diving, some aspects of cave diving, and several of the new tools I think bear looking at for the scientific diving community because it just makes our job easier.

More than half of you people here are already members of AAUS so I will not elaborate on this. The American Academy of Underwater Sciences basically sprung into existence in 1976 under a different name. The reason it was started was because there was a real concern within the scientific diving group that the OSHA commercial diving standards would include scientists. The sport diving community was on the ball right when that came out, and got together with the national training agencies and said, "We are sport divers, and not commercial. We have different tasks." They were exempted.

The fact that the scientific group did not get exempted caused six years of really hard work, lots of hearings, paperwork, statistics, and data analysis to prove that we were a self-regulated, very safe organization, and we did not really need any governmental control or regulations from the outside. So the final rule came out in 1982, of what a scientific diving program must be. All of that information is in our Standard.

One of the products, the main product of the Academy, is a continual peer review of our manual. This manual is really a consensual standard of what scientific diving programs around the nation are doing. It is continuously reviewed. There are several statistics committees that look at these things. Membership input is urged, etc. It is basic guidelines.

Some people just are not joiners; you do not have to join. But if you call your program a scientific diving program and think you are exempted from the OSHA commercial diving standards, you need at least to adhere to these minimum guidelines. The best way to be able to change things if they are not right is to try to do it from the inside and not from the outside.

Since the commercial exemption for the scientific diving group was granted we have really focused back onto underwater science. We have had our annual symposium at the Scripps Institution from 1981 to 1984 and in 1985 we had a joint international diving symposium with the scientific community. In 1986 we went to Florida State University in Tallahassee. Last year we were at the University of Washington in Seattle. This year we are going back to Scripps.

We are a small group. We have 250 individual members. A lot of those people are diving officers, so they represent another whole group at their home institution. What has really enhanced the whole thing is an organizational membership. By joining they recognize that their program actually does comply.

We have also been looking at a lot of practical things that can help the diving scientist in the field and can help the diving officers run their programs. Some of those in the past have been surface supplied diving, and Dudley run a nitrox diving workshop in a symposium two years ago.

In Seattle we had a lot of interest and demand for information on cold water diving. You know you have some people like Jim Steward who have been diving in the Antarctic and things like that, but it is not really in print. We got experts together. We looked at several things, logistics, personal training and so forth, all of those things.

Basically what we are up to is to disseminate information. We have proceedings from the past symposiums. We try to get them out at the annual symposium each year.

We have two projects this year. One is, we are looking at funding from the National Science Foundation to run a five day workshop each year for the new groups going to the Arctic and Antarctic. It will be based on information we have gathered in the past and at the annual symposiums.

We are also looking at a workshop to get additional information on dive computers. We will look at some of the algorithms, how they are used, how applicable it is to scientific diving, and we will try to come up with guidelines.

Discussion by Mr. Louis Riccio:

Another bit of high technology diving equipment relevant to enriched air diving is the closed circuit rebreather. Mr. Riccio is an engineer with Biomarine, Inc., manufacturer of the rebreather units used by the U.S. Navy and of interest to special purpose divers and this Workshop.

MR. RICCIO: The company making the rebreathers for the last few years has been Rexnord. As of last week we have gone back to the original name of Biomarine. New ownership has taken place, the company is now part of Gas Services Offshore, Aberdeen. We are continuing under the name Biomarine, Incorporated.

As background, we have dedicated ourselves as a closed circuit rebreather company right from the beginning in 1969. It was a spinoff of the aerospace industry in the mid sixties by a group of engineers that left General Electric. General Electric was involved in life support equipment. They did analyses of the atmospheres that the space astronauts would be exposed to. So some of the spinoffs were developed in the mid-1960's.

One thing that came up was zero g simulation. What are the reactions of man in space going to be? How is he going to work with a restricted space suit on? One way to simulate zero g was by water immersion. So one of the ideas we had as an advanced manned systems group was to devise a way to put man under water breathing with a closed circuit rebreather. It had a pump on it to pressurize the space suit and we had a diaphragm in there as a counterlung because he was under pressure.

The idea was to put him on a closed circuit rebreather because there would be no bubbles, and that way they would not have any bubbles for orientation. We balanced the astronaut out for simulation of zero g. Now this is set up in Huntsville as a necessary training program for all astronauts. We helped to pioneer that.

The idea of closed circuit being in a nice neat package suggested that maybe the Navy would have a use for this because of their extended missions and new developments. We put together a prototype and they said they would take a look at it.

The first rig that really was in production was the Mark 10; that is the closed circuit rebreather from General Electric Company, and that was in the year 1970 to 1971.

Essentially what we [Biomarine] did was to make improvements on the breathing bag and the scrubber by combining the two systems in the same housing. Using a flexible rubber diaphragm in a fairly compact mechanism we made the CO_2 scrubber and the diaphragm all in one. We came out with a very efficient CO_2 scrubber, and it was closely associated with the hot breathing gas and so it made the scrubber work. They each benefit each other for keeping the breathing circuit warm. The first CCR-1000's are in this configuration. In effect the scrubber and the diagram are located in the middle of the back and the two bottles and the electronics are in the lower section.

We were working with other diving systems at the time also. And we did an on-board bibs, really a closed circuit emergency breathing apparatus, from parts drawn out of the CCR-1000. It has a controller to monitor and control the PO_2 setting.

Then we branched into making analyzing equipment. We had low alarm, high alarm set points, and some of this equipment went into the medical industry.

In our simplest form we had an oxygen analyzer with a galvanic cell that could be put directly into a sampling line. It operated at low pressure, but it was direct reading and a very simple analyzer.

We are in Malvern, Pennsylvania, a suburb of Philadelphia. We have about 45 to 50 employees. The current project is the Mark 16, the Navy's current closed circuit breathing apparatus, and the Mark 15 also is still active in the Navy, so we are supporting that.

We are accredited by the Standard Quality Assurance Program, and all of our parts are quite highly inspected. We have a government inspector on site who lives there to see that everything is right.

We have a sensor lab where we continually try to upgrade the O_2 sensor. We are working on keeping the standards up and making it better.

Some other products are still closed circuit rebreathers but are geared for fire fighting. We have a one-hour closed circuit pure oxygen unit, with of course no control or sensors at all. It just feeds pure O_2 into the center section at a certain rate, 1.2 liters per minute. We have a number of other units, one and two hour durations, for "HAZMAT" and mine reserve service. Our current "civilian" diving unit is the CCR-155. It uses some Mark 16 components. The unit will last 12 hours in warm water; in colder water it can be as low as four to five hours. Lights show the O_2 level, and there is a secondary backup meter to give you an accurate upgrade of where the batteries are and where your sensors are.

And we have a pure O_2 rebreather, the CCR-25, designed for military operations, shallow diving, commando or special forces groups. It is back mounted and has really a low silhouette.

Some of the units are being used for a Navy flyaway team, a team put together at EDU. They have the whole diving system in flyaway containers, with the mixing gas all set up, and they can fly away to an emergency, say a downed plane. The system is used for 300 fsw dives, with heliox.

The missions we were given to design and build the equipment for are military, and the idea now is to develop less complicated units. So I am here to listen to some of the needs. There is a possibility that we can get into some very exciting programs in the future.

MR. PARKER: So you do have plans or potential for designing a "cheaper" unit?

MR. RICCIO: I think if the missions go out, then we can tailor it. Some of the conversations these past couple of days have led me to believe that there is a need. We have to weigh the idea; if the numbers are there, then the need is there.

Chapter V. Workshop wrapup: Prospects for enriched air nitrox diving

Discussion by Dr. R.W. Hamilton:

DR. HAMILTON: I would like to start off with a brief review of the high points of the various talks, to try to pull some of it together.

Dudley Crosson started it off with an optimistic note that scientific diving is entering a new growth phase, but he also pointed out that we are almost in the 21st century and are still using mid-century diving techniques, for the most part. At least some of us are.

And he reeducated me right away about what scientific divers do, specifically that they normally do not do diving with decompression stops; that was a bit of useful information, though not new. It has been modified slightly during the Workshop, but for the most part there seems to be a strong interest in avoiding decompression stops completely.

He then carried through with the central question of the Workshop, "Is the equivalent air depth concept valid?" We have had a number of different approaches to answering that question. I think it can be dismissed in summary by saying, yes, from a physiological point of view that seems to be the case. There seems to be ample experience from a variety of sources that backs that up.

I also learned something else new here, that there are really three ways to classify enriched air nitrox diving. First you use a set table, with a fixed mix such as the Nitrox I Tables in the NOAA Manual. Or you can use what is called the equivalent air depth, the EAD concept, which means you do not stick with just one gas or just one table, but you have the opportunity to make your best mix and go to an "optimal" decompression table taken from a standard air table and using the equivalent air principal, the EAD. The third one is to use a "custom" table. This uses the same sort of mixtures, and enriched air mixture, but here you have a decompression profile that is calculated for the specific situation, optimized for depth and gas.

There does not seem to be very much difference in the way they work physiologically. It depends very much on the table that you use.

There was a concern expressed about letting all of this high tech information fall into the hands of sport divers, because they will get themselves in trouble. We just heard Dick Rutkowski summarize that situation. There seems to be no way that we can keep them from doing it. We might as well share the information and do the best we can and let them get proper training and proper mixes and so forth, so that if they are going to do it, they can do it in a safe manner. If they do not, it is going to kick back on all of us.

In my talk I had the opportunity to review the technology in general. I pointed out the possibility of using helium. If your mixing principles are such that it does not cost you anything more to use helium, there are some situations where that might be an advantage.

situation, it does not seem to be something that will affect the scientific diving community very much.

Also, I pointed out that the thermal reservations about using helium (it is believed to cool the dives more than air) are probably not entirely valid, although it seems from further comments made during the course of the meeting that some people still believe that. If I had real hard data on that topic I would be happy to share it with you. My thoughts are based on the best interpretation we can get, a little bit of information and some calculations.

We also talked a great deal about oxygen. Although Dr. Lambertsen rightly did not like my use of the word "chronic," we have two levels of oxygen we have to worry about, the CNS limit, and whole-body effects of longer exposures.

We have heard about the CNS limit repeatedly throughout the seminar. I offered a suggestion that some colleagues and I have worked out for the management of longer exposures. Some people here are, it appears, still struggling with the old Navy procedures.

I believe that we now have something we can work with, the Repex method. It is covered in the NOAA reports [references after Hamilton paper], something that is accepted by the government--one part of the government, anyway--that will give you an opportunity to use a different approach to those exposures below 1.5 atm or below the CNS range.

Jim Clark gave us a lot of information on that subject in the range deeper than 1.5 atm. It boils down to the fact that your oxygen limit is going to depend greatly on what equipment you are using or what the circumstances are--how hard you are working, or basically how much carbon dioxide is in the background. A limit that might be quite acceptable under one circumstance might not be somewhere else.

There seems to be a general consensus among this group that diving with a PO_2 of about 1.6 atm is acceptable. I would endorse that, although I would not dive all day at 1.6. There has to be a time limit to it. I would not advocate a higher limit in this community. Maybe commercial or military agencies might have occasion to do something different, but for the university, or the oceanographic institution like HBOI, there is no point in going much beyond that, in my opinion. That seems to be pretty much the opinion of most of the people that talked about it at this Workshop. What I mean to say is a level of 1.6 atm is okay for a few minutes, and that very short exposures to higher levels would be acceptable.

So, for CNS toxicity, I did not have the feeling that there is a lot of disagreement or confusion on the subject, even though slightly different numbers were mentioned. Everybody, I think, appreciates the fact that it depends on the circumstances, the kind of equipment one is using, and, of course, very much on individual characteristics. This is an important topic for this kind of diving; it sets the depth limit.

Morgan told us about the history of nitrox diving within NOAA, a long record. Dick Rutkowski just reviewed it. It goes back to the middle 1970's or perhaps earlier. The advantages have been obvious for a long time. Andre says he was using it in 1957.

Dr. Lambertsen and other physiologists--Dr. Behnke, Dr. Lanphier, and others--learned a long time ago that oxygen is one of the best ways to improve decompression. That is the substance of why we are here.

Dick Rutkowski mentioned it and Dr. Lambertsen confirmed that there was some concern about things said here finding their way into rules and regulations. That is always a concern, but Dr. Lambertsen's point is well made that different organizations have different needs. Simply because someone says something at a Workshop does not mean that your organization will have to pick it up. But again, that is something that takes a little bit of judgment. I think we are on the right track.

Andre Galerne pointed out to us why, in his opinion, nitrox did not take off early in the commercial field; it took a while. As Terry Overland just told us, it has matured.

Andre pointed out that for one thing people did not really know how to do it. They were not sure it would work. The uncertainty about the "equivalent air depth" principle was greater a few years ago than it is now. Because he had the technique, Andre quite rightly did not feel it was necessary for him to tell his competitors how to do it. Therefore, they "bad-mouthed", the idea because they could not do it. So there were things operating within the industry to keep it from being picked up. It has fortunately made some strides in the right direction.

I know of another project of some 4,000 dives in addition to the 7,000 or so that Terry reported on. Andre has done, I guess, many thousands of enriched air dives.

We discussed the question of the role of inert gas in oxygen toxicity: The question asks whether inert gas does play a role, whether it is necessary, whether it has an effect. Everybody agrees that it probably does not have a significant effect at the cellular level; what inert gas does is change the "environment" of the oxygen. That is, if a person is breathing a high density gas mixture, he is likely to have more trouble eliminating carbon dioxide. It is agreed and well established that CO_2 increases sensitivity to oxygen. Dr. Lambertsen mentioned that the brain gets a higher dose of oxygen during exercise, because during exercise there is more carbon dioxide in the body and that tends to dilate the blood vessels in the brain. So, in fact, you have a change in the environment.

The other question, the central question, is, "What is the effect of oxygen?" It is very much a matter of the particular situation.

Regarding the limits for oxygen with pure oxygen as used by the Navy, I think nobody else but the navies use pure oxygen while working in the water; the U.S. Navy is very strong to discourage others from using it. You are breathing a fairly low resistance mix in very shallow water, and in that circumstance the limit can be higher than you would want to put on an oxygen/nitrogen mixture used in deeper water. That may explain in part why the Navy has two different sets of limits.

We next heard from Dave Dinsmore about the very well organized and well controlled enriched air diving program at the University of North Carolina at Wilmington. Although it is relatively young in experience with enriched air nitrox, I think that group is taking a fairly exemplary approach to how it can be introduced into a scientific diving operation.

They talked about mixing and its problems. Morgan Wells also told us about mixing. That is always going to be a problem with this kind of diving. You should pay attention to that.

We did not solve the mixing problems here, we just talked about the fact that they exist.

Dick Vann did a superb job of working out the physiology of enriched air diving and of reviewing the physiology literature on the subject of the "equivalent air depth." There are a number of papers in the literature that deal with this, many of them oriented towards animals. He found one paper with human work that in my mind seem to settle the issue, the study by Weathersby (NMRI 86-97) which incorporates quite a number of data points and shows essentially no effect. It is a very flat curve with no effect of PO_2 and a very equal effect of enriched air and air alone. This provides a quotable bit of information that helps show that the equivalent air depth is a valid physiological concept.

In a lot of the papers he discussed the problems that where found or the differences that were found were in the range where the oxygen was well above 1.3 or 1.4 atm. In almost everything above 2.0 atm the EAD principle did not seem to work, and almost every deviation seen was associated with an oxygen level at least that high. There is a good reason for that; it represents a different environment.

Basically, when you have that much oxygen the oxygen has a physiological effect on the body. It works well beyond its role as a mechanical gas or as a replacement for the inert gas. Some of that effect can be beneficial. We know when we treat people that oxygen seems to have a therapeutic effect well beyond what it does by simply replacing the inert gas.

The message here is that the physiology is reasonably complicated when you get in the higher ranges of oxygen, but they are outside the range in which we are operating. We can leave that to the physiologists, and concern ourselves with the fact that we have some problems of teaching how to do it, making divers stay within limits and tables and making the procedures uncomplicated enough to be used effectively without creating a hazard themselves due to complexity.

We have heard about diver-carried decompression computers; with or without logging capability, these would make enriched air a lot easier to use, and I expect that the next time this group convenes to talk about this subject we will have something like that available.

The point was made by Dick Vann, essentially the same thing that others have said, that the equivalent air depth is still not going to do you much good if your original table is not good. That is an important point.

There was a question raised about the term "oxygen bends," because some people had talked about that in the literature. Dr. Lambertsen set us straight on it, that you do not really get bends from oxygen. Oxygen can perhaps contribute, under certain circumstances, to a decompression, but it is not very easy to have something that could properly be called oxygen bends (See Thalmann, 1987). I agree that this is just not a very good term to use.

Claude Harvey told us very nicely about what the Navy was doing in view of the equipment and the tables. The Navy has been doing this kind of diving, but in their own way.

I for one was educated here again. I had not really thought about how much better the Navy's style of diving matches the scientific diver than it does the commercial diver. The commercial divers are way off on one end, and the Navy and scientific divers have a lot of things in common.

MR. STANTON: Maybe because the "Scientists in the Sea" program linked the universities to the Navy in the early 1970's.

DR. HAMILTON: No, I think it is because of what they have to do and how they do it. There are plenty of links between the Navy and commercial diving also. In fact, in the early days everybody in commercial diving was Navy trained except Andre; he did some things differently from the way some of the other companies did them.

But the fact is the kind of diving the Navy does includes a lot of scuba and surface oriented dives. There is very little deep sea or bell diving. So the kind of diving that the Navy does is very similar to the kind that scientific divers do and the problems are the same. This had not occurred to me, but when he pointed it out it suddenly became obvious. The Navy accepts the equivalent air depth, uses it, and sees no great problem with it.

Dick Vann made a good point when he mentioned that one of the most important contributions to diving decompression work that has come along in a long time has been the analytical method developed by Paul Weathersby to do statistics on various profiles. This method allows one to do a common analysis on a variety of different profile types; that has given us a really good insight into things. But nothing has come from that that shakes our faith in EAD.

Dick also pointed out that individual differences are very important, and that empirical testing is how we make progress.

Ron Nishi told us a little bit about some of the Canadian programs, particularly the new breathing equipment. He showed us his analysis of the extremely complex problems that come up from having a piece of equipment that changes the PO_2 when you change the level of exercise as well as when you change the depth. Those are problems that I had not really thought about. Sometimes other people have to deal with things that we just do not even know about.

The limits of that kind of equipment are not decompression. They are the limits for PO_2 toxicity, scrubber duration, temperature, diver endurance, and things like that. One can make a case that rebreathers really belong in this kind of program, that it is a natural extension of enriched air diving to go into more controlled enriched air or other high oxygen special mixes that allow this to be done in a more efficient way.

And as we have just discussed, one of these days I hope Paul Heinmiller and his colleagues will come up with a dive computer system to enable us to optimize the whole thing in real time. Also, we need to know more than we do. One of the ways a program like this will help is to feed back information.

So in summary I feel like we have learned a great deal here (I certainly have). I think we have met our objective, in that we have taken this particular kind of diving and spread it out and picked it apart and looked at it from a wide variety of perspectives. We have zeroed in particularly on the kind of diving that the scientific diving community needs, and I do not think we found any nasty surprises. We have found some nice opportunities that still yet need to be developed.

I am pleased to see new institutions bringing these methods into their programs, and I am going to leave here with a very good feeling about both the programs and what we have learned about them.

DR. CROSSON: A question I have asked several other people is, "Where do we go from here?"

DR. HAMILTON: In a way I just answered that. Where do we go from here? One thing is that new groups will pick up on what is beginning to be an established technology. This is exemplified by what the North Carolina people and NOAA have put to use.

What IUC, Oceaneering, and the Navy have done is perhaps not all that relevant to what scientific diving organizations are doing, but that experience--thousands of dives with minimal problems--puts the methods in good perspective for the scientific diving organizations that are just getting into it with their diving control boards.

So one new thing that is going on is that at least three groups here have the problem of bringing enriched air/nitrox diving on line; fortunately we have some groups that have been doing it to learn from.

To carry on with my answer, we did not find any nasty surprises. I think we have a pretty good basis for what we are doing.

The next thing of what is coming, ways in which expansion can be made, is the use of special equipment that can supply these different mixtures, and the development of decompression procedures to deal with that.

Even though decompression is largely what it is all about, I sort of like the idea that we have been able to get into a position where decompression is not the limiting factor, where one can plan a mission and deal with other things such as cold and scrubbers. Ron Nishi mentioned the rebreathers that he is working with.

It is not that way yet for the scientific diver. Decompression and the time you are allowed on a dive is still an important part of it, although when you are working with open circuit scuba you may not have all that much gas available so that is another limit.

It has been pointed out several times here and many times before that oxygen is the best way to improve the decompression situation. We have talked here about the hazards of oxygen and about ways to use oxygen to improve decompression. What I see that could come along this line is an expansion in terms of more creative looks at the way to decompress by a manipulation of gases and by a manipulation of the decompression parameters themselves. That of course is balanced off against the added complexity and the difficulty of operating or keeping control of something when you have all of these options.

As much as people like Ron and Dick and I like to be creative on this sort of thing, when you really get down to the bottom line you have to make it as simple as you can in order to keep it under control.

So regardless of how creative we may get, there is going to be that "keep it simple" force that tends to pull it back. I am certainly not going to argue against it, because that is what makes diving safe. In fact, our Medical Board at Harbor Branch has pointed out that sometimes being more conservative does not necessarily make your operations safer if the conservatism boxes you into a complicated operational problem.

Such a thing would be something that could make your decompression a little more efficient but which at the same time would cause a great deal of confusion and require more training and so on is not necessarily going to be of benefit.

Another thing yet to come along with special mix dive computers, is a good and inexpensive dive logger so that we can learn from what we are doing better than we do now. Most diving people keep logs, but the logs may differ from what was done. Recall the figure that Dick Vann showed of what the diver thought versus what the logger thought. When we get loggers, we can learn much better what we have.

DR. CLARK: I would like to emphasis a couple of points that Bill made regarding oxygen limits, and make a fervent plea. I think an outer limit for oxygen exposure has been very well defined by Butler and Thalmann with their closed circuit oxygen diving. I think at this stage of our knowledge it is appropriate to say that 1.6 atm is a reasonable upper limit that we can live with; it gives you plenty of room to work, from what I have heard over this last day and a half.

Now, at 1.6 atm at 20 fsw Butler and Thalmann show that with one exception of a susceptible diver they went four hours with no toxicity at all. That is well beyond what you are doing here. I think that forms an outer limit. You are not going to do better than that. You should never expect to do better than that on a mixed gas dive. We are a far cry from being able to say you can do that well.

The fact is, there have been no carefully controlled objective studies of oxygen tolerance during nitrox diving, in the nitrox kinds of conditions. The very early work of Lanphier where problems were found is impossible to interpret because of the CO_2 retention in those divers. So, in effect, we have no information.

As I said during my talk, to get lab information directly relevant to this would take years and millions, and it probably will never be done. In lieu of that we can get information from the field. Many of you are already doing it, 1.6 atm for maybe an hour, maybe more than an hour. Please begin to log this information. Each exposure is an experiment that is not at all likely to be repeated in a laboratory under controlled conditions. Especially in diving logs where you have accurate information on the depth and the time, please accumulate this information and publish it. That is useful.

DR. HAMILTON: I second that. Different groups are beginning to put together methods of accepting this information and doing something with it. I am working with the Canadian government on a data base oriented to commercial diving, and we hope soon to have a data base mechanism that can be used for this sort of thing by different institutions. Certainly there is the one at the University of Pennsylvania. We would like to see everything remembered. When you have a stack of dive logs that you are getting ready to throw out, call up Dr. Lambertsen or me or somebody before you throw them out. We learned with agony about a whole bunch of logs that had been thrown out just before we got our program going.

Diving changes, so we need the fresh stuff because what somebody did in the fifties with the equipment they had and with those limits is not necessarily going to help us very much. It will not help us nearly as much as what you are doing right now.

MR. STANTON: Can I suggest that there already is a mechanism in place for such data collection. The universities that belong to AAUS are required to submit annual reports with dive log information. They have to collect it.

DR. HAMILTON: Does that include individual dive profiles though?

MR. STANTON: Yes.

MR. PARKER: We maintain all of that. A lot of it is the typical square profile.

DR. HAMILTON: One thing about the square profiles is that they are easier to analyze.

MR. PARKER: I mean, you go to a 20 and 30 foot depth and you sit there and watch a crab go through its behavioral patterns.

DR. HAMILTON: Just to know what people are able to do with no problems is of help.

CAPT. HARVEY: Dick and several others made passing remarks as to training, education, safety standards, teaching people to do as safely as possible things that they are going to do anyhow. I would suggest that for the future we need to get some of these people to publish this and get it out where it is more readily available as a start towards standards. When PADI was created, and NAUI and many of the organizations back in the fifties, that was their purpose. We have to make sure it is getting out. We heard tales about people that were doing things on their own. The way we can combat that is to make sure that you guys that are doing the teaching get it published and spread around.

DR. HAMILTON: That is a very important point. Even though what Dick Rutkowski gave us was a commercial pitch, we still have to remember that it is people that have accidents. Very rarely is an accident due to pure equipment failure that was not itself set up by somebody not checking it or not putting it together right, or after that not reacting properly to the failure.

The diving inspector the British sector of the North Sea took over when there was a real bad record a few years ago. A lot of divers were being lost, and he took a good look at the situation and ended up with a very clear conclusion that it was people that were causing the accidents, and that it was a lack of competence and professionalism in those people. He made a definitive effort to improve competence and improve the professional attitude in the diving in the North Sea, and it almost totally stopped the accidents. Now they are almost as professional as the airlines, or at least they have gone a long way towards doing that. The safety record reflects it except for an occasional serious mistake. The diving accident rate just zoomed down and has stayed fairly low over several years of diving.

Many of you are all in the training business anyway. At a university, training is your job, and you know how to do it; that really is important. People are the ones that have the accidents.

MR. LANG: Another extension of what Claude said about the need for a basic manual is reciprocity of programs. Somebody that is trained in scuba from the University of Washington can go without too many hurdles and dive with other programs. The manual really can be traced back to the original Scripps manual, which is probably why such a similarity between the Navy and scientific diving activities in terms of equipment use and things like that. The first course was taught at Scripps in 1959 and most of the other programs around the country all were derived from that.

When the reciprocity issues such as the nitrox diving programs start coming up in these different universities and people start working with each other, I think it will be a big plus to not have to have them go through the entire course again but to recognize their training as part of the reciprocity issue.

MR. HEINMILLER: This is anecdotal and not all encompassing. Some of the people that are out there that are going to be using nitrox for sport diving are related to this guy in a case I was just involved in. He trains instructors and has a dive store and he knows the Navy has a book on diving but he does not even know what it is called.

DR. HAMILTON: What he is saying is that there is a problem with some of the people that are doing training themselves in that they do not know what is going on as well as they should, and it is up to you people to fix that.

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