FOA

FOA Rapport
C 50068-5.1
Oktober 1989
ISSN 0347-7665

OXYGEN ENRICHED AIR - "NITROX" - IN SURFACE ORIENTED DIVING

Hans Örnhagen[1], and R.W. Hamilton[2]
[1] FOA 58 Naval Medicine, S-130 61 Hårsfjärden, Sweden
[2] Hamilton Research Ltd, Tarrytown, NY 10591, USA

Försvarets Forskningsanstalt
Huvudavdelningen för Mänsklig Prestation och Funktion
102 54 Stockholm

FOAs RAPPORTKATEGORIER

Rapporter avsedda för spridning utanför FOA utges i följande kategorier:

A-rapport. Huvudsakligen för totalförsvaret avsedd och tillrättalagd redovisning av ett, som regel avslutat, vetenskapligt arbete. Förekommer som öppen (A-) och hemlig (AH-) rapport.

B-rapport. (FOA Reprints). För vidare spridning avsedd redovisning av öppet vetenskapligt eller tekniskt-vetenskapligt originalarbete av allmänt intresse. Arbetet publiceras i tidskrift, som distribueras som särtryck under benämningen *"FOA Reprints"*. Förekommer som öppen (B-) rapport.

C-rapport. För spridning inom eller utom FOA. Redovisning av arbete t ex i form av delrapport, preliminärrapport eller metodikrapport. Förekommer som öppen redovisning av vetenskapligt eller tekniskt-vetenskapligt originalarbete av allmänt intresse. Förekommer som öppen (C-) och hemlig (CH-) rapport.

E-rapport. Redovisning av arbete föranlett av främst FOAs civila uppdragsforskning. Förekommer som öppen (E-) och hemlig (EH-) rapport. Uppgift om kategori E eller EH på skriftlig redovisning (rapport) av arbete skall regelmässigt anges i uppdragsavtal.

FOA-RAPPORTS STATUS

Författare svarar för rapportens innehåll, t ex för att angivna resultat är riktiga, för gjorda slutsatser och rekommendationer etc.

FOA svarar – genom att rapporten godkänts för utgivning som FOArapport – för att det redovisade arbetet utförts i överensstämmelse med "vetenskap och praxis" på området i fråga.

I förekommande fall tar FOA ställning till i rapporten gjorda bedömningar etc. Detta anges i så fall i särskild ordning, t ex i missiv.

REGISTRERING

FOA-rapport skall registreras enligt nedanstående exempel:

FOA-rapport
A1-82-2345-M6(E4)
ISSN 0000-0000

där

A	är rapportkategorin
1	är utgivande havd/Ck (6=Ck)
82	är utgivningsåret
2345	är löpnr (inom resp kategori och havd/Ck (6=Ck)
M6(E4)	är den(de) programdel(-ar) dit rapporten i första (andra) hand kan hänföras
ISSN nr	är en internationell numrering av seriella publikationer

Försvarets Forskningsanstalt
Huvudavdelningen för Mänsklig Prestation
och Funktion
102 54 Stockholm

FOA Rapport
C 500068-5.1
Oktober 1989
ISSN 0347-7665

OXYGEN ENRICHED AIR - "NITROX" - IN SURFACE ORIENTED DIVING

Hans Örnhagen[1], and R.W. Hamilton[2]
[1] FOA 58 Naval Medicine, S-130 61 Hårsfjärden, Sweden
[2] Hamilton Research Ltd, Tarrytown, NY 10591, USA

Sändlista:
CM, FMV-Ubåt,STU, AGA Gas, Alfax, ASS, CTH-Undervattensteknik, COMEX-Marseille, DIB, DSH, Dykskol-KA 1, GUSI-Gestacht, Helsedirektoratet-Oslo, HMS Belos, Ingenjörer för UV-teknik-Lund, INM-Portsmouth, KI-Baromedicin, KS-Klinfys, Marinens Dykarskola-KÖS, MDC, MS/Dyk, MS/Läk, NHC-Aberdeen, NOAA, NUTEC-Bergen, Oljedirektoratet-Stavanger, PLAB, Statens Dykkerskole-Bergen, STENA Offshore, SYR, UHMS, Yrkesdykarföreningen.

Issuing organization
National Defence Research Establishment
Department of Human Studies
102 54 Stockholm

Document name and doc. ref. No.
FOA Rapport C 50068-5.1

Date of issue
Oktober 1989

Item designation
535131

Project name (abbreviated if necessary)

Author(s)
Hans Örnhagen
R W Hamilton

Initiator or sponsoring organization
STU

Document title

Oxygen enriched air - "Nitrox" - in surface oriented diving

Abstract

The use of breathing mixtures richer in oxygen than air has been shown to allow longer working times for a diver than is possible with air alone. This method, called "enriched air" or "nitrox" diving, has been used extensively and successfully in some cases, but there is still some concern about its validity.

In order to make the decompression and safety advantages of enriched air nitrox diving available to the Swedish diving community we have performed a study of the background of the method, its history and its hazards, and have carried out a test program simulating a representative series of commercial working dives with extensive biomedical monitoring and assessment of diver tolerance of the method. The main advantages of enriched air diving accrue from mixtures of 30 to 50% oxygen used over the depth range of about 12 to 40 msw depth; the possibility of oxygen toxicity limits the range in which the method can be used. Special decompression schedules can be used, or they can be derived from existing air tables for shallower depths according to the principle of "equivalent air depth." We found no evidence in the literature that this is not valid, and some careful experiments have supported it. Central nervous system oxygen toxicity is avoided by working at a PO_2 of 1.4 bar or less, and longer duration toxicity of the lung and body in general can be managed by an empirical schedule of exposure limits worked out from laboratory and field experience. With proper regard for oxygen safety the gas mixtures can be mixed in advance or on line using "blenders" designed for this purpose, and most kinds of breathing equipment can be used; rebreathers for military use have been a source of much relevant experience.

The tests with 8 commercial divers involved 7 consecutive days of chamber diving at 21 msw witha 50% oxygen, 50% nitrogen mixture for 220 min/day. This was intended to test the decompression procedures and be slightly beyond proposed oxygen exposure limits over enough days duration to validate the method for most commercial jobs. Extensive pulmonary, exercise, and biochemical monitoring produced a few changes, most of them anticipated, but nothing to indicate that the method should not be considered acceptable for commercial use.

Key words

Diving, mixed gas, oxygen, nitrox, occupational medicine

Notes

Further bibliographic description

Language
English

ISSN 0347-7665

ISBN

Pages 80

Price

restricted distribution
unclassified

Distributor (if not issuing organization)

Dokumentets utgivare Försvarets Forskningsanstalt Huvudavdelningen för Mänsklig Prestation och Funktion 102 54 Stockholm	Dokumentnamn och dokumentbeteckning FOA Rapport C 50068-5.1 Dokumentets datum: October 1989 Uppdragsnr.: 535131 Projektnamn (ev förkortat)
Upphovsman(män) Hans Örnhagen R W Hamilton	Uppdragsgivare /Sponsorer STU Arbetsmiljöfonden Svenska Byggbranschens utvecklingsfond(SBUF)

Dokumentets titel

Dykning med nitrox.

Huvudinnehåll

Nitrox dvs luft med extra oxygentillsats har använts för dykning sedan 60-talet. På 70-talet gjorde Svenska Marinen i samarbete med AGA prover med en gasblandare för nitroxdykning med s k tung utrustning dvs hjälm med friflödessystem. Svenska civila yrkesdykare har vid enstaka tillfällen använt dykmetodiken.

Föreliggande rapport har tillkommit som ett resultat av ett önskemål från DSH (Delegationen för samordning av havsresursverksamhet) och DIB (Dykentreprenörerna i Byggentreprenörerna) att metodens för- och nackdelar samt eventuella yrkesmedicinska risker belyses.
Rapportens första del utgör resultatet av en litteraturgenomgång. Nitroxdykning kan användas med fördel i djupområdet 12-40 m med 30-50 % O_2. Så kallad oxygenkramp undvikes om PO_2 maximeras till 1.4 bar. Lungskador minimeras om den dagliga oxygendosen begränsas enligt föreslagna beräkningsförfarande.
Andra delen av rapporten beskriver en vid MDC genomförd serie om 56 mandykningar till 21 m med 220 min expositionstid där 50 % O_2, 50 % N_2 används och som föregicks och följdes av omfattande medicinska kontroller. Inget framkom som skulle tyda på att den föreslagna metoden inte skulle vara lämplig för yrkesmässigt bruk. Det är dock föreslaget att de dykare som dyker med nitrox skall genomgå mer omfattande medicinska undersökningar än vad som föreskrivs enligt Arbetarskyddsstyrelsens anvisningar 86:8

Nyckelord

Dykning, blandgas, oxygen, nitrox, yrkesmedicin

Anm

Övriga bibliografiska uppgifter	Språk: Engelska
ISSN 0347-7665	ISBN
Omfång 80 sidor	Pris
Sekretessuppgifter	

Distributör (om annan än ovan)

ABSTRACT

The use of breathing mixtures richer in oxygen than air has been shown to allow longer working times for a diver than is possible with air alone. This method, called "enriched air" or "nitrox" diving, has been used extensively and successfully, but there is still some concern about its validity.

In order to make the decompression and safety advantages of enriched air nitrox diving available to the Swedish diving community we have performed a study of the background of the method, its history and its hazards, and have carried out a test program simulating a representative series of commercial working dives with extensive biomedical monitoring and assessment of diver tolerance of the method. The main advantages of enriched air diving accrue from mixtures of 30 to 50% oxygen used over the depth range of about 12 to 40 msw depth; the possibility of oxygen toxicity limits the range in which the method can be used. Special decompression schedules can be used, or they can be derived from existing air tables for shallower depths according to the principle of "equivalent air depth." We found no evidence in the literature that this is not valid, and some careful experiments have supported it. Central nervous system oxygen toxicity is avoided by working at a PO_2 of 1.4 bar or less, and longer duration toxicity of the lung and body in general can be managed by an empirical schedule of exposure limits worked out from laboratory and field experience. With proper regard for oxygen safety the gas mixtures can be mixed in advance or on line using "blenders" designed for this purpose, and most kinds of breathing equipment can be used; rebreathers for military use have been a source of much relevant experience.

The tests with 8 commercial divers involved 7 consecutive days of chamber diving at 21 msw with a 50% oxygen, 50% nitrogen mixture for 220 min/day. This was intended to test the decompression procedures and be slightly beyond proposed oxygen exposure limits over enough days duration to validate the method for most commercial jobs. Extensive pulmonary, exercise, and biochemical monitoring produced a few changes, most of them anticipated, but nothing to indicate that the method should not be considered acceptable for commercial use.

TABLE OF CONTENTS

ABSTRACT

PART ONE:

PHYSIOLOGICAL AND OPERATIONAL CONSIDERATIONS

I INTRODUCTION 11
- A Objective 11
- B Description of enriched air nitrox diving 11
- C Decompression and the "equivalent air depth" 11
  - 1 Decompression savings 11
  - 2 Improved decompression reliability 13
- D Oxygen exposure 13
- E Other diving techniques 13

II HISTORY 13
- A Military interest in nitrox 14
- B Enriched air nitrox in commercial diving 14
- C Nitrox in scientific diving 16

III DECOMPRESSION 16
- A Physiology 16
- B Methods for determining decompression 17
  - 1 EAD (Equivalent Air Depth) 17
  - 2 Enriched air nitrox tables 18
  - 3 Custom tables 18
  - 4 Dive computers 18
  - 5 Repetitive diving 18

IV OXYGEN 18
- A Physiology of oxygen toxicity 19
- B Central Nervous System (CNS) toxicity 19
  - 1 Limits 19
  - 2 Factors that modify susceptibility 20
- C Whole-body, including pulmonary toxicity 20
  - 1 Rationale 20
  - 2 Oxygen Tolerance Units (OTU) 21
  - 3 Whole-body limits 21
  - 4 Dealing with individual differences 26

-eceding page blank

V MIXING METHODS 27
A Mixing equipment and methods 27
1 Prepared mixtures 27
2 On-line mixing using gas blenders... 29
3 Diver-worn rebreathers 29

B Breathing equipment 30

C Handling oxygen 30

PART TWO:

BIOMEDICAL EVALUATION OF 7 DAYS OF ENRICHED AIR NITROX DIVING

I INTRODUCTION 31
A Rationale for performing the tests 31

B Test considerations 31
1 Laboratory or field 31
2 Maximum PO_2 during a dive 31
3 Maximum daily oxygen dose 31
4 Overall exposure duration 32
5 Decompression stress 32
6 CO_2 load 32
7 Divers 32
8 Synopsis of test schedule 32

C Medical evaluation and monitoring 32

II METHODS 33
A The dive series 33

B The divers 33

C Diver environment 33
1 Breathing equipment 33
2 Breathing gas 34
3 Temperature 34
4 Oxygen exposure 34

D Daily and in-dive monitoring 34
1 Pulmonary function 34
2 Interviews and questionnaires 35
3 Doppler bubble detection 35

E Medical exam pre/post dive series 35
1 Exercise tests 35
2 Pulmonary function 35
3 Pulmonary diffusion capacity 35
4 Neurology 36
5 Hematology 36
6 Tests without available results 36

III RESULTS.. 37
A Daily and in-dive monitoring........................... 37
1 Questionnaires........................... 37
2 Doppler................................... 37
3 Spirometry................................39

B Hospital measurements pre/post dive series...........39
1 Pulmonary function.................... 40
2 Exercise tests............................ 41
3 Neurology.............................. 42
4 Blood......................................42

IV DISCUSSION...43

V CONCLUSION.. 43

VI RECOMMENDATIONS FOR THE FUTURE............... 44

REFERENCES... 45

APPENDIX... 51
A Individual test results.................................... 51

B Copy of the report from the project group to the sponsoring organizations (in Swedish)............... 59

PHYSIOLOGICAL AND OPERATIONAL CONSIDERATIONS

I. INTRODUCTION

A. *Objective*

This project has the objective of providing a firm rationale for the introduction of modern oxygen enriched air or "nitrox" diving procedures for commercial and military use in Sweden. Enriched air nitrox can improve efficiency of certain modes of diving; it has been used for some time and in various settings, but neither the details of the method, the track record of its use, nor the biomedical effects have been well documented. This project is intended to address these needs. First, the leading technical approaches and procedures are described and analyzed. Next, a test program has been carried out to validate a typical commercial work pattern; this covered decompression, work schedules, and the physiological and medical effects of the exposure.

This report is intended as a comprehensive coverage of the topic, but it is not a procedures manual or "cookbook," nor does it in any way presume to set formal standards.

As Appendix B is enclosed a copy (in Swedish) of the report from the project group to the sponsoring organizations.

B. *Description of enriched air nitrox diving*

"Oxygen enriched air" or "nitrox" diving is a method for reducing a diver's decompression obligation by using as a breathing gas a mixture of air and oxygen, with the effect that some of the nitrogen in atmospheric air is replaced with oxygen. Because of limitations of exposure to elevated oxygen the method is usable only in the depth range down to about 40 msw (msw--meter of sea water, as a unit of pressure--is defined as 1/10 bar or 10 kPa), and its advantages are not significant shallower than about 12 msw. The special requirements of using the method are determining the decompression, avoiding the effects of oxygen toxicity, and preparation and handling of the needed gas mixtures.

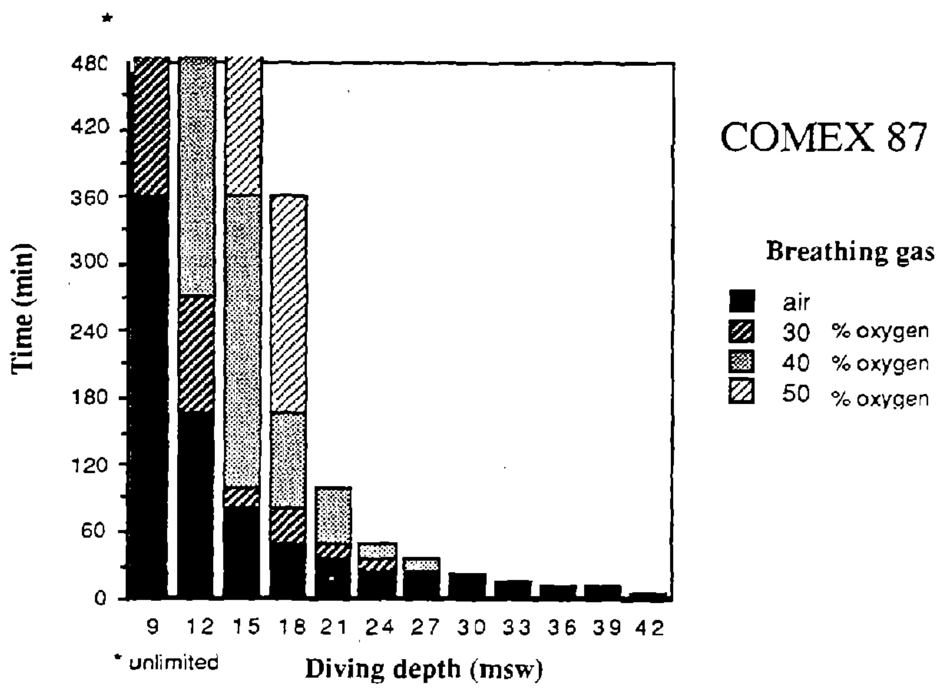
The term "nitrox" is used also to describe mixtures used in nitrogen-based saturation diving, in which the mixture is one with less oxygen than air. In this report "nitrox" refers to the enriched air mixture, although limiting its use to the "unriched" mixture is preferred by some.

C. *Decompression and the "equivalent air depth"*

In order to take full advantage of the lower nitrogen level in the enriched air or nitrox mixture an adjustment has to be made in the decompression time. Nitrox diving has been practiced for some years by use of a principle called the "equivalent air depth." This is a principle--or assumption--that only the inert gas need be considered in a decompression. The "EAD" is a calculation of the depth of an air dive that has the same nitrogen partial pressure as the dive to be made with an oxygen-enriched mixture; the air dive will be for a shallower depth, and will thus require less decompression time.

1. *Decompression savings*

This shorter decompression table for the equivalent air depth is then used for decompressing from the deeper nitrox dive. In Figures 1 and 2 are seen the increases in maximum exposure time before direct ascent when using nitrox with 30, 40, and 50% oxygen. For example, note that as much as 7 times more no-stop bottom time is allowed at 18 msw when using a mixture of 50% oxygen; 50% air, than when using air. The slight difference in maximum exposure times between Figures 1 and 2 depends on the difference in required decompression between the Comex and Swen-88 tables on which these graphs are based (Imbert & Bontoux, 1987; Hamilton, Muren, et al, 1988).



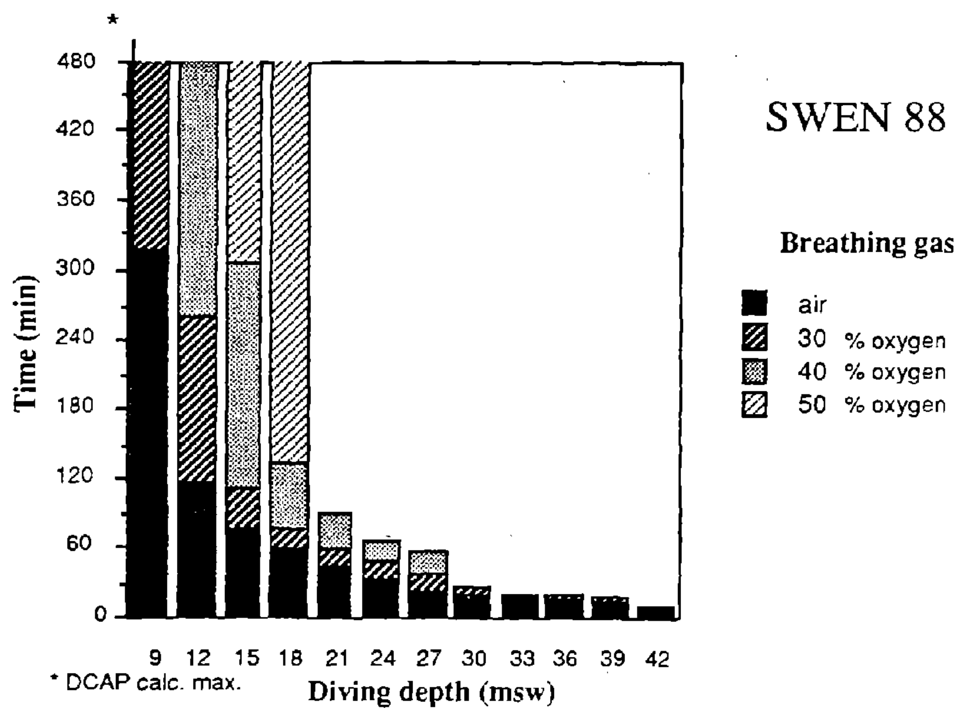


Figure 1 and 2. Maximum no stop time (min) versus depth (msw) for different breathing gases, using COMEX 87 (fig 1) and SWEN 88 (fig 2).

2. Improved decompression reliability

Not only are the nitrox decompression times shorter, it appears from theory and from both operational and physiological experience that the decompressions are likely to be more reliable, involving a slightly lower risk of decompression sickness. One reason for this is straightforward in cases where there are decompression stops. While the decompression time for a given dive will be shorter based on a shallower equivalent air depth, the decompression stops will also be taken with a higher oxygen level, and this will make them more conservative. In addition, the reduction of decompression time reduces overall decompression stress for a given bottom working time (Hamilton R W, D J Kenyon, R E Peterson, 1978); this is the same principle that most sets of decompression tables are more reliable in the shorter, shallower dives that in longer, deeper dives.

However, a decompression based on equivalent air depth will in general be subject to the same decompression risks as the original air table used for determining the equivalent dive.

D. Oxygen exposure

"Nitrox" diving invokes a concern about both of the traditional types of oxygen toxicity, the CNS toxicity that can lead to epileptic-like convulsions when oxygen is breathed at too high partial pressures for short times (several minutes to tens of minutes), and the longer term effects primarily on the lungs due to breathing oxygen at lower but still elevated doses for longer periods (several hours to days). Oxygen toxicity can be avoided in nitrox diving by use of proper techniques, principally by limitation and timing of the exposure.

E. Other diving techniques

The use of oxygen enriched air during diving is but one of several methods of improving efficiency in diving through reduction of decompression time. Some of these involve inwater oxygen decompression, surface decompression with oxygen, pure oxygen and mixed gas rebreathers, saturation, and saturation-excursion diving. Although some of these may offer advantages as great as enriched air diving they each pose a separate set of problems, and are not addressed in this report.

II. HISTORY

While nitrox diving has been practiced extensively for some years, documentation of its use is relatively limited. This is due largely to the fact that many of the applications require relatively little in the way of detailed written procedures, and even where such procedures have been prepared they are mostly internal unpublished documents or simple algorithms for selecting the proper table. The results have often been unexciting in terms of reportable incidents. In commercial use there has been no great incentive on the part of the companies using these special techniques to tell the details to competitors, and the competitors would hardly be eager to be complimentary about an exotic procedure that offers their competitors an advantage.

We are not aware of the earliest use of nitrox diving, but the benefits of replacing some of the inert gas with oxygen was well understood by early decompression researchers such as J.S. Haldane. Galerne reports commercial use of nitrox methods as early as 1957 (Galerne, 1989).

A. Military interest in nitrox

As leaders in the development of both techniques and equipment for diving, various navies have done work with nitrox diving. There has always been an interest in improving decompression, but in most cases military development has been related to the use of various diver-worn breathing devices. Although not identified as such, use of enriched air mixtures dates back at least to the 1915 version of the U.S. Navy's diving manual (Stillson, 1915).

The Swedish Navy began work with nitrox methods in the early 1960's. In two series of dives reported by Muren (1973; plus internal navy reports by Muren 1970.10.29 and 1973.04.18) divers breathed from an AGA on-line nitrox mixer. This was a prototype that was not produced. Some dives were done in the pressure chamber in the 20-30 msw range for bottom times up to 3 h, to test primarily the tolerance of the divers to the oxygen level and to look for a buildup of CO_2; some others were done at sea. Few really taxing decompressions were performed. One result was that the divers felt their work was easier when they were breathing the mixtures higher in oxygen. The Diving Manual of the Royal British Navy includes a section on EAD, but it is quite conservative and offers little operational benefit or information on the reliability of the concept.

Although the U.S. Navy does not do air-equivalent diving today, it is seriously interested in "nitrox" as these mixtures are used in rebreathers. A substantial multi-year program dedicated to the development of both a diver carried decompression computer and the algorithms to program it has been reasonably successful in providing these for "special warfare" swimmers, and just as important has provided improved knowledge about nitrogen/oxygen decompression (Thalmann, 1984; Thalmann, 1986).

Another extensive air/oxygen decompression development program has been carried out by the Canadian Forces and DCIEM. This has led to a new and highly regarded set of air decompression tables with some special features like inwater oxygen decompression, surface decompression with oxygen, diving at altitude, and repetitive diving, but the only interest in nitrox tables and techniques again seems to be devoted to the special decompression problems of rebreathers (Nishi, 1989).

B. Enriched air nitrox in commercial diving

Because it results in more efficient ways of performing diving work commercial companies have adopted nitrox diving techniques. As mentioned earlier, in many cases this has not been highly publicized because of competitive motives; there was no point in telling the competitors how to do it. In some countries only specific decompression tables are authorized for use in commercial diving, and this has limited the use of nitrox.

Where the technique has been used its use has in some case been extensive, and the results have been uniformly good. In 1982 the F. Selmer construction company employed nitrox techniques for installing a pipeline landfall near Kallstø, Norway (Hartung, 1982; Bøe and Hartung, 1983). Some 4500 dives were performed, without significant DCS (decompression sickness) problems. The EAD procedures used in these dives were included in a set of tables primarily dedicated to surface decompression, published by Arntzen and Eidsvik as a NUTEC report (1980); Arntzen also reported use of a combination of nitrox and surface decompression, again with excellent results (1986); in one group of 1809 dives there was only one case of DCS reported.

The AGA blender evaluated in 1970-71 by the Swedish Navy has been in commercial use by the Swedish diving company DYKAB. A typical set of dives performed by the company is given in Table 1. The important thing about this series is that it represents a documented use of nitrox techniques, with a reasonable oxygen exposure and without significant problems with either oxygen or decompression. The diver reported typical symptoms including some numbness in fingertips and toes and some reduction of physical working capacity on weekends towards the end of the series of dives.All dives were done by a single diver using a prototype AGA blender at a partial pressure setting of 1.5 bar PO_2. The oxygen toxicity dose is discussed below in the section on oxygen toxicity.

Table 1

An example of accumulated nitrox dives for a construction diver at 20 m.

Dat week of the year	No of dives	Total exp. time (min)	Total decomp. time (min)	Total OTU	Remarks
20	3	99	12	198	
21	8	383	32	793	
22	7	392	24	789	
23	11	719	42	1447	
24	10	382	32	796	
25	4	248	16	492	
					Vacation 4 weeks
30	4	146	-	284	
31	5	284	-	542	
32	16	443	-	873	
33	14	617	16	1227	
34	2	106	-	208	
35	5	380	15	755	
36	2	98	-	198	
37	2	135	3	282	

Andre Galerne of IUC says he began diving with nitrox in 1957 and has used it repeatedly since then whenever the situation justified it (Galerne et al, 1984; Galerne, 1989). One specific case was a job in high current where it was hard to maintain depth during decompression; this situation was handled nicely by getting rid of the requirement for decompression stops. Another application he reports is to use enriched air for dives at high altitudes.

In a summary of the enriched air nitrox diving activities of Oceaneering International, Overland (1989) reports a series of some 7000 nitrox dives in 1982-83. These were mostly in the North Sea, and were mostly performed with fixed mixes, 40 % oxygen to 30 msw and 32.5 % to 40 msw. These used a PO_2 of 1.6 bar, which has worked for OI and is their limit for the working depth. Mixing was with the Dräger Polycom 101 blender, which mixes oxygen and air and is used with a backup bank of either compressed air or the mixture in use. Most dives have been done in the range 21 to 30 msw. Overland reported that they had no problems with either oxygen toxicity or DCS.

C. *Nitrox in scientific diving*

Oxygen enriched air diving is the subject of considerable current interest in the scientific diving community in the U.S. The institutional scientific divers are strictly regulated by their own organization.

Scientific diving rarely exceeds 40 msw and most is done at depths less than 20 msw. Virtually all such diving is done with scuba, and almost all dives are within the no-stop decompression limits. Because of the no-stop limits there is a strong incentive to use oxygen enriched air techniques to increase bottom time. The leader in nitrox diving among scientific divers in the U.S. is NOAA, the National Oceanic and Atmospheric Administration, which published it's first manual in the 1970's (NOAA Diving Manual, 1979; Wells, 1989). The NOAA manual contains procedures and tables for diving with a mixture of 32 % oxygen, 68 % nitrogen, which is designated as "NOAA Nitrox I." The tables are direct conversions from the standard USN air tables using the principle of equivalent air depth (EAD); their format is the same as that used by the USN air tables so it is familiar. A few test dives were performed before the tables were issued, but the result have not been published--possibly because of lack of interest since they revealed no problems with the method. However, field use of these tables has proven satisfactory in thousands of dives, and they are considered operational. NOAA plans to offer Nitrox II soon, a mix with 37.5 % oxygen. Although the NOAA Diving Office provides some specific tables and mixes, they also use and endorse the EAD principle.

A number of institutional and scientific diving programs have added enriched air nitrox to their programs (Crosson, 1986; 1987). They use both the "fixed mix" method of NOAA and the EAD method where other mixes are preferable. Because these programs are all scuba oriented a major procedural and training factor exists in preparing mixes, and in fact the mixing of high pressure gases rich in oxygen is regarded as significantly more dangerous than the diving with these mixes (Dinsmore, 1989; Rutkowski, 1989).

Recreational divers eager to increase their bottom time without decompression stops are showing increased interest in nitrox. It is now possible to purchase NOAA Nitrox I (32 %) mixture in specially labelled scuba tanks, and there are several courses offered to train divers and diving operations managers in nitrox diving methods (Rutkowski D, 1989).

III. DECOMPRESSION

This section is the heart of enriched air nitrox diving. An improvement in decompression is the motivation for the method. This improvement appears in several ways. It allows longer dives for a given decompression, and it also yields a "cleaner" diver, one less likely to develop DCS when compared with the same diver using air. This saving carries over to operations, where the ability to complete a job with one dive, for example, that might otherwise take two or three not only affords a substantial cost saving but is safer overall.

A. *Physiology*

The theoretical basis of enriched air diving is that a diver can be decompressed based only on exposure time and the partial pressure of nitrogen breathed, and that the oxygen component need not be considered. This principle is called the "equivalent air depth." It has been practiced more or less at face value by extensive commercial diving projects, but it is not known how closely these dives approached the theoretical limits (Arntzen, 1986;

Galerne, 1989; Overland, 1989). A set of tables calculated on this basis has been published in the NOAA Diving Manual (1979) and has been in use for some years without significant problems (Wells, 1989).

Berghage and McCracken using rats tried to test the equivalent air depth principle (1979 a; 1979 b). Their conclusion was that it should be questioned, but if one looks at the data the only animals that had a higher incidence of DCS were those exposed at well above the oxygen levels allowed by the proposed procedures. Vann (1989) explains this as a function of oxygen extraction; when the oxygen is at "physiological" levels the amount remaining in the tissues is almost insignificant, but at higher levels there is enough oxygen remaining for it to be effective as an inert gas. In addition, high PO_2 has a prominent effect on blood flow in tissue and this could also play a role (Lambertsen, 1987). Earlier work by Rashbass and Eaton (1957) using rats showed agreement with the EAD at up to 2.2 atm PO_2.

In early USN work Logan (1961) made dives with the same PN_2 but at high and low PO_2, and had 2 cases of DCS at the higher PO_2 and one at the lower, but he had far to few data points to produce a statistically significant difference.

Weathersby and colleagues put this to the test in a series of very tightly controlled human dives (1987). The results showed absolutely no "error" in the EAD principle in 477 dives at varying depths, comparing dives with oxygen at 10 to 12 % to others at 30 to 40 %. Monitoring was especially strict, making this one experiment an excellent justification for the method. Vann has performed a thorough review of the literature relevant to the EAD, and concludes that there is not enough evidence to warrant abandoning the EAD theory (1989).

In a different approach, another USN investigator, Thalmann (1986), considers that oxygen may play a role and has modified his E-L algorithm to account for this gas in the case where there is more oxygen present than normal metabolism would be expected to consume. Whether this is valid or not is not likely to be an issue with enriched air diving because the PO_2's used are not expected to be high enough to show this effect.

B. Methods for determining decompression

It seems clear from work discussed in the previous section that the decompression can be based solely on the inert gas partial pressure; there are three general ways to do this. These are to use the equivalent air depth as a method of determining the decompression, to prepare and perhaps publish tables for specific situations, or to prepare the tables needed for a specific job on a "custom" basis.

1. EAD (Equivalent Air Depth)

As mentioned in the general discussion, a decompression can be planned based on the equivalent air depth. The EAD formula calculates the depth in msw that has the same nitrogen partial pressure with air as the dive depth has with the nitrox mix, and the table appropriate for this equivalent depth can be used for decompression. The EAD is calculated according to the following equation:

$$EAD = \frac{(1 - FO_2)\ (D + 10\ \text{msw})}{0.79} - 10\ \text{msw}$$

where FO_2 is the fraction of oxygen in the inspired air, 0.79 is the fraction of nitrogen in air,
D is depth of the dive in msw, and 10 msw is the number of msw in one bar. Atmospheric pressure is considered to be one bar. For example, if a diver is breathing 40% oxygen at 22 msw the EAD is ((1-0.4) (22+10) /0.79) - 10. or 14.3 msw. For a one hour dive at 22 msw the next deeper Swen-88 table for 24 msw requires 39 min decompression time, but using the table for 15 msw no decompression stop is required.

2. *Enriched air nitrox tables*

An alternative to the EAD method is to use one or more fixed mixtures and specific nitrox tables; these are usually calculated on the EAD concept.

The table approach offers more operational convenience and fewer places to make a mistake, but where the mixture is not optimal they are not as efficient as can usually be arranged using the EAD method.

3. *Custom tables*

The most efficient decompressions can be planned where the capability for direct calculation of decompression tables of proven reliability is available. In this case the mixture can be selected as optimal for the depth and desired working time, and the table calculated for just that situation.

4. *Dive computers*

Several types of diver-worn computer are available for short-duration diving in the air range. At present none is available that can be set for a non-air gas mix. When such a device based on a properly conservative model becomes available it could be an outstanding tool for nitrox diving.

Whatever the method used for determining decompression, its efficiency will depend in part on how close the gas mixture approaches the optimum tolerance level of oxygen. Optimal mixtures can be prepared by means of a variety of mixers, as discussed below in the section on mixing methods.

5. *Repetitive diving*

Repetitive dives may be made with nitrox according to the rules for the air dives, using the equivalent air depths. That is, the repetitive designation is determined for the air-equivalent first dive, the one that was carried out, and the air-equivalent second dive is reduced appropriately. In a study devoted primarily to evaluating the basic tables, Leitch and Barnard (1982) demonstrated that repetitive dives seem to follow the EAD principle.

IV. OXYGEN

Oxygen is a gas that has to be within limits; there has to be a certain amount to maintain life processes, but too much can be toxic in a variety of ways. The possibility of oxygen toxicity plays an important role in the planning and conduct of diving that uses higher than normal oxygen levels, and although it can be managed, using it requires special care. This section covers these topics.

A. *Physiology of oxygen toxicity*

The physiology of oxygen as a poison has been reviewed historically in great detail by Clark, and Lambertsen, 1971), and by Shilling et al (1976). Clark has recently performed a more recent review specifically directed at oxygen enriched air nitrox diving (Clark, 1989). The objective here is to avoid oxygen toxicity as a problem, and this can be made more logical by considering a few aspects of its physiology. The important aspects are the major toxic effects, time relationships, reversibility, and factors that can modify the basic limitations. Despite the fact that hyperoxia is rare in nature, evolution seems to have dealt with oxygen as much as a toxin as the basis for metabolism, and anti-oxidant biochemistry is apparently universal in all living things. The implication of this is that the anti-oxidant factors are continuously being created but exposure to elevated oxygen levels depletes them. Managing oxygen toxicity while taking advantage of high levels of it in diving requires good timing. A well understood application of this is the use of intermittent oxygen breathing--air breaks--to allow relatively high oxygen levels to be used in treating DCS. Higher levels of oxygen lead to toxicity more quickly, but even short periods of reduced PO_2 can postpone problems. This applies to both of the major types of toxicity, CNS and "whole body." The proposed methods of managing oxygen take this into account.

B. *Central nervous system (CNS) toxicity*

CNS toxicity, which has as its end point a convulsion, is the most serious threat. Although numerous divers have survived convulsions in the water, many have not. The hazard is drowning or mechanical injury; oxygen convulsions themselves do not appear to leave lasting aftereffects. Convulsions can come without warning, and although there may be warning signs of an impending convulsion, they cannot be relied on to avoid occurrence. The approach recommended here is to stay well out of the zone where convulsions are at all likely. The rationale for it is covered in more detail elsewhere, for example in the Repex reports on nitrox saturation diving and the recent workshop on scientific nitrox diving (Hamilton, Kenyon, and Peterson, 1988; Hamilton, Kenyon, et al, 1988; Lambertsen, 1988; Hamilton et al, 1989).

The U.S. Navy Diving Manual in the section on mixed gas diving has a widely recognized table of oxygen limits (USN, 1981). These limits, the "normal" rather than the "exceptional," are generally regarded as conservative, and indeed they are both conservative and appropriate in the part of the exposure range that deals with CNS toxicity; these limits are recommended here. On the other hand, exposure to PO_2's at 1.5 bar and below is not dealt with appropriately by the USN table; a new algorithm for dealing with non-CNS limits-- generally lumped with "pulmonary" effects in the literature but which covers more than just the lung--is included in the subsequent section on pulmonary or somatic (whole-body) toxicity.

1. Limits

Stating the CNS limits can be so brief that it does not justify including a table here. CNS toxicity under normal diving conditions is quite unlikely below 1.5 bar (Clark, 1989; Butler and Thalmann, 1984; 1986), so this can be used as an upper limit for routine work. The time limit for exposure at 1.5 bar and lower is based on physiological factors other than CNS toxicity. Routine working exposure at levels higher than 1.5 bar should be limited to no greater than a PO_2 of 1.6 bar at any time, and this for a relatively short time; the USN table just mentioned allows up to 30 min.

2. *Factors that modify susceptibility*

A number of modifying factors affect the susceptibility to CNS toxicity, and if present can alter the levels that are properly chosen as limits. An important exacerbating factor is CO_2, which increases blood flow in the brain, and which can be affected by a number of other factors such as work level, breathing resistance, gas density, inherent CO_2 retention, and other conditions that allow CO_2 to increase (Piantadosi et al, 1979; Clark, 1982). CO_2 distributes rapidly through the body, so it is not important to make a distinction between, for example, lung or arterial levels, but some adjustments should be made in the tolerable oxygen exposure times or PO_2 levels if CO_2 is elevated. Increased body temperature also may make a diver more susceptible to convulsions.

If the operating conditions cannot be kept within normal limits we suggest incorporating deviations by some ARBITRARY "rules of thumb." These have to be more or less arbitrary because of the lack of precise knowledge of either the conditions or their effectiveness. For example, a helmet CO_2 level of 1% [or 1.5%] can be accepted as the normal situation, but for each 1/2% above that the tolerance time at 1.4 bar might have to be reduced by a number of minutes and the maximum oxygen partial pressure threshold reduced . Other deviations should be handled in a similar manner. Some caution should be used in relying too much on arbitrary limits.

C. *Whole body, including pulmonary toxicity*

1. *Rationale*

The second primary type of classical oxygen toxicity along with CNS is pulmonary. The toxic effects of longer exposures to lower levels of oxygen than cause the CNS effects just discussed are effects on the lungs. One of the best currently available indicators of the degree of lung toxicity is a reduction in vital capacity (Clark and Lambertsen, 1971; Shilling et al, 1976). VC is the amount of air that can be exhaled from a full inspiration; it is reduced by the lung irritation that results from exposure to toxic levels of oxygen over periods of hours to days. This reduction is the result of inflammation and edema formation in the lung tissue. It is usually accompanied by chest pain and coughing, but these symptoms may not appear until after measurable changes in VC have taken place.

Extensive animal studies and clinical observations have not revealed any indication that pulmonary changes of the sort encountered in diving (and hyperbaric oxygen therapy) are not completely reversible. (Crosbie et al, 1982; Hyacinthe et al, 1981).

There are other effects of oxygen exposure in addition to those on the lung and CNS. Among these are paresthesia, headache, numb fingertips and toes, and a reduced aerobic capacity. Other effects, including effects on the eye, come with still higher doses than those just mentioned. (Clark, 1982). Because of the generality of these effects it might be more appropriate to call them by a broader term than just pulmonary. Since the symptoms are widespread throughout the body they might be called "somatic," but a more palatable term is "whole body." The use of the term "chronic" to describe this syndrome is maybe inappropriate (Lambertsen, 1989), because "chronic lung oxygen toxicity" already is applied to a condition that can result from weeks of exposure to oxygen as in an oxygen tent. This condition, which is not relevant to this project, can result in fibrosis of a permanent nature, whereas the VC changes and other somatic symptoms encountered in the shorter exposures used in diving appear to be completely reversible (Eckenhoff, 1987; Miller, 1981).

There is another interaction between high oxygen levels and CO_2. Oxygen affects the transport of CO_2 by the blood (transport is inhibited by saturation of hemoglobin by O_2) and consequently CO_2 can build up slightly in the body tissues as a result of breathing high oxygen, but the effects of this are presumed to be already included in the proposed algorithm for managing oxygen (Lambertsen et al, 1987).

There are other benefits of breathing a mixture higher in oxygen. One is that the lungs and body contain more oxygen and would allow a few more seconds, even minutes, for a diver to deal with an emergency loss of breathing gas or mask. Also, it has been shown that endurance of a hard working diver breathing against the resistance of a typical demand type breathing apparatus may be increased at a PO_2 of 1.5 atm compared with his normal 0.21 atm (Peterson et al, 1979).

2. *Oxygen Tolerance Units (OTU)*

Because oxygen exposure acts somewhat in the same manner as exposure to other toxic agents or to drugs, it seemed reasonable to Lambertsen and colleagues at the University of Pennsylvania to try to establish a method of measuring or monitoring the "dose" of oxygen as a means of controlling exposure. It was clear that toxicity builds up faster at higher exposure levels, but the dose did not seem linearly related to exposure level. Using vital capacity as an indicator of the effect of the exposure, this laboratory developed a method of monitoring oxygen dose (Bardin and Lambertsen, 1970; Wright, 1972).

Vital capacity changes take place gradually and at different rates in response to different oxygen levels. It takes patience and a lot of training to be able to measure VC changes in the ranges needed--for example, reductions of less than 10 %--but Lambertsen and colleagues were able to predict vital capacity changes as a result of the "dose" of oxygen exposure over a time interval in the range from a few to several hours (Shilling et al, 1976, Clark, 1982). This method, called the "cumulative pulmonary toxicity dose" (CPTD) considers a pulmonary toxicity "unit" (a UPTD) to be an exposure of 1 min at 1 atm PO_2 (i.e., 1 bar). Units accumulate at a faster rate at levels above 1 bar, and at a slower rate below that (but see Harabin et al, 1987). A more recent term having the same value is Oxygen Tolerance Unit, OTU (see below).

3. *Whole-body limits*

Empirical measurements have been used to fit the curve of dose accumulation (VC changes) to different exposure levels of time and PO_2. Because other symptoms occur and other parts of the body are affected, we feel a term not limited to "pulmonary" might be preferable. Even so, the traditional "unit" serves as a suitable basis for long term oxygen exposure management. The equation relating oxygen toxicity units to PO_2 level and duration of exposure is a power function,but it can be reduced to a simple chart showing the number of units (OTU's) per minute of exposure at different PO_2's. This is shown in Table 2, and graphically in Fig 3.

The CPTD method is an accepted way of determining a dose of oxygen exposure, but what to do with it is not so well accepted. This is due to the fact that recovery takes place when exposures are low, but there is nothing in the calculation to account properly for recovery (Hills, 1976; Harabin et al, 1986; Renie, 1987). A maximum CPTD of 615 has been suggested, but the time period for which this is a tolerable exposure is not clear (Wright, 1972).

Table 2.

Oxygen toxicity rate (OTU/min) at different PO_2

PO_2 (atm)	OTU (/min)	(/h)
0.6	0.26	16
0.7	0.47	28
0.8	0.65	39
0.9	0.83	50
1.0	1.0	60
1.1	1.16	70
1.2	1.32	79
1.3	1.48	89
1.4	1.63	98
1.5	1.78	107

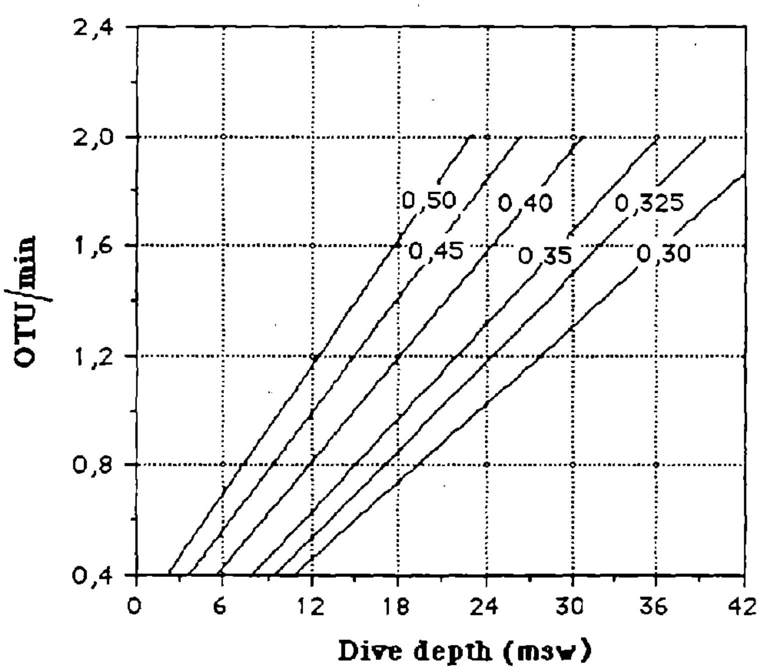


Figure 3. Oxygen Tolerance Units (OTU)/min versus depth (msw) for different oxygen fractions.

A possible solution to this dilemma has been developed for managing oxygen exposure in divers making air excursions from an underwater habitat (Hamilton, Kenyon, and Peterson, 1988; Hamilton, Kenyon, et al, 1988; Hamilton et al, 1989). Inspired primarily by the work of Sterk and colleagues (Sterk and Schrier, 1984; Sterk, 1986; 1987) but based on an assortment of data from many sources, the Repex approach uses the UPTD--called here OTU, for Oxygen Tolerance Unit--as the unit of measure. Although the original toxicity units were considered only to predict immediate and short duration effects of hyperoxic exposure on VC, the algorithm seems to work quite well for multi-day exposures if assessed against the appropriate limits.

The important characteristic of the Repex approach to managing oxygen toxicity is that the tolerable dose of oxygen is a function of the duration of the exposure. That is, the average daily recommended dose depends on the number of days of exposure. For long duration exposures (more than about 10 days) the Repex method calls for an average of about 300 OTU per day. This would allow slightly more than 400 units per day on the basis of a 5-day week. For a single day, with no exposure on the days before and after, the allowed dose is 850 units. This higher dose is acceptable because exposure is presumed to be over and the damage threshold is not reached; the diver can then recover. The Repex exposure limits proposed for use with nitrox diving in Sweden are given in Table 3 and Fig 4.

Table 3.
Allowable daily oxygen doses

Exposure (mission) duration, (days)	Avg daily dose (OTU)	Total this mission (OTU)
1	850	850
2	700	1400
3	620	1860
4	525	2100
5	460	2300
6	420	2520
7	380	2660
8	350	2800
9	330	2970
10	310	3100
11	300	3300
12	300	3600
13	300	3900
14	300	4200
15-30	300	as req

The figures in table give guidelines for management of long-duration oxygen exposure. The average daily dose predicted to be tolerable is given in the second column for various mission durations; the tolerable daily level or average daily dose is a function of how many days exposure are involved. Here "mission duration" is the number of days of exposure to increased PO_2. The 3rd column gives the total allowable exposure for the full missions defined in the first two columns. The dose covers the entire period of a dive when $PO_2 > 0.5$ atm.

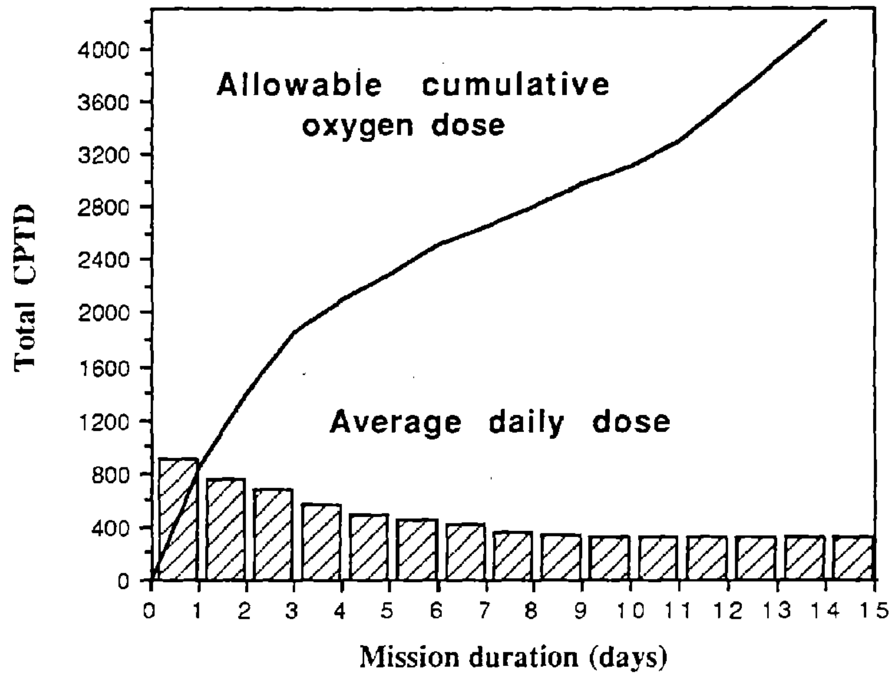


Figure 4. The maximally allowed daily oxygen dose (shaded bars) and allowable cumulative oxygen dose (line) according to Hamilton et al 1988.

The concept of setting the daily exposure dose to be a function of exposure duration seems sound. The exact daily dose to be used for a given diving situation is still subject to modification on the basis of additional operational experience controlled with this method. It is based on most of the available data on long duration exposures to high oxygen, and has been shown to be workable, but refinements may be needed after extended use so the limits should not be considered cast in concrete. The overall picture of the daily allowed exposure is given in Figure 4.

The dose for a single day is an exposure that has been shown many times in deep commercial bounce dives to be operationally acceptable. That is, an occasional person will feel mild symptoms, but there is still enough "oxygen time" remaining for a DCS treatment using Treatment Table 6 without exceeding an average 10% decrease in vital capacity.

Exposures for periods of from 2 to about 10 days have decreasing values as the number of days of exposure increases, tapering down to a daily dose of about 300 OTU. The exposure for 2 days is 1400 OTU, a daily dose less on the average than for a single day, but still much more than would be allowed if the long term value were used. The allowed daily dose is the average for an exposure period, not a cumulative value. That is, if a diver has received 850 units the first day his second day can only be 550 units in order to stay within the proposed limits. It should be emphasized that this example is for a diver who starts fresh and will have a few days of rest after the exposure; if exposure is to be continuous for many days then the dose for that period has to be used.

For divers working in daily hyperoxia the average dose of 300 OTU per day can be considered over a 5-day work week, making the daily dose equal 420 units. Sterk (personal communication) is currently using 400/day for a 5-day week. A chart for planning OTU's for different depths and mixes is given in Table 4.

Table 4.
Example of oxygen toxicity rate (OTU/min) at different depths (msw) and different oxygen fractions.

Depth	0,3	0,35	0,4	0,45	0,5
9	-	-	-	-	0,9
12	-	-	0,79	0,98	1,16
15	0,6	0,79	1,00	1,22	1,40
18	0,73	0,97	1,19	1,41	1,63
21	0,88	1,15	1,39	1,63	1,86
24	1,03	1,31	1,56	1,82	2,07
27	1,17	1,48	1,75	-	-
30	1,32	1,63	1,93	-	-
33	1,47	1,79	-	-	-
36	1,60	1,99	-	-	-
39	1,73	-	-	-	-
40	1,78	-	-	-	-

An example of PO_2's and EAD's for different oxygen fractions and depths using Comex 87 tables is shown in Table 5. This table also shows the maximum allowable exposure time before direct ascent for air breathing and the use of nitrox with 30, 40, and 50% oxygen.

Table 5.
Example of enriched air advantages using Comex 1987 tables with 30, 40, and 50 % O_2

Dive depth (msw)	PO_2 (atm) 30%	PO_2 (atm) 40%	PO_2 (atm) 50%	Calculated EAD (msw) / **Table EAD (msw)** 30%	40%	50%	Maximum exposure time before direct ascent (min) air	30%	40%	50%
9	0,57	0,76	0,95	6,8	4,4	2,0				
				9	**6**	**3**	360	•	•	•
12	0,66	0,88	1,10	9,5	6,7	3,9				
				12	**9**	**6**	165	270	•	•
15	0,75	1,00	1,25	12,2	9,0	5,8				
				15	**9**	**6**	80	100	360	•
18	0,84	1,12	1,40	15,0	11,2	7,7				
				15	**12**	**9**	50	80	165	360
21	0,93	1,29	1,55	17,5	13,5	9,6				
				18	**15**	**12**	35	50	100	165
24	1,00	1,40	1,70	20,1	15,8	11,5				
				21	**18**	-	25	35	50	-
27	1,10	1,50	1,85	23,0	18,1	-				
				24	**21**	-	20	25	35	-
30	1,20	1,60	2,00	25,4	20,4	-				
				27	**21**	-	15	20	35	-
33	1,30	1,70	2,15	28,0	22,7	-				
				30	-	-	10	15	-	-
36	1,40	1,84	2,30	31,0	-	-				
				33	-	-	·10	10	-	-

Using the DCAP program and Swen-88 tables customized nitrox tables can be calculated. Table 6 gives an example of maximum exposure time before direct ascent for different depths and nitrox mixtures.

Table 6
Examples of enriched air advantages using SWEN 88 tables with 30, 40, and 50% O_2.

Dive depth		PO_2 / Max exposure before direct ascent		
msw	21%	30%	40%	50%
9	0.40 / 320	0.57 / ∞	0.76 / ∞	0.95 / O_2 dose
12	0.46 / 110	0.66 / 260	0.88 / 480	1.10 / O_2 dose
15	0.53 / 75	0.75 / 110	1.00 / 300	1.25 / O_2 dose
18	0.59 / 55	0.84 / 75	1.12 / 130	1.40 / O_2 dose
21	0.65 / 40	0.93 / 55	1.29 / 90	-
24	0.71 / 30	1.00 / 45	1.40 / 65	-
27	0.78 / 25	1.10 / 40	-	-
30	0.84 / 20	1.20 / 30	-	-
33	0.90 / 15	1.30 / 20	-	-
36	0.97 / 10	1.40 / 20	-	-

4. Dealing with individual differences

The individual difference in sensitivity to oxygen toxicity affects the optimal use of high oxygen doses. No attempt has been made to define rigid limits, and we would prefer to regard our recommendations as guidelines to be refined later. This is for two reasons. First, we may not really know the best values to be used for the different levels; these will be modified as new data accumulates and more existing data is found. But there is also a large aspect of individual sensitivity (Harabin et al, 1987). That is, there is a big difference in the reaction of different individuals to an exposure. A large difference in the sensitivity of a single individual on different days has also been observed.
Abundant evidence exists that if an exposure is too high and symptoms develop they are reversible. In fact, most experienced divers have experienced the numb fingertips, tingling, occasional chest pain or lung irritation, headaches, and reduction of aerobic capacity that accompanies a long treatment for DCS on a dive or dives that required a lot of oxygen breathing. If a diver has too many symptoms then his daily dose should be reduced. The contrary, allowing a diver to increase his individual dose, is a more difficult situation to regulate, but because the consequences of an excessive exposure are minor then there is not much risk involved and the benefits of flexibility are great. This is not the same as decompression, where the consequences of a failure of the method (the tables and procedures) can be far more serious.

V. MIXING METHODS

This section covers the operational aspects of enriched air nitrox diving as they relate to preparing, handling, and breathing the special gas mixtures, and especially to the use of correct practices in handling oxygen and oxygen enriched mixtures.

A. *Mixing equipment and methods*

There are several methods of preparing enriched air mixtures. These all require at least some special equipment, and in some cases these are complex and can represent significant investments. The methods include preparation of pre-mixed gas, on-line mixing, and use of rebreathers.

1. *Prepared mixtures*

The simplest method of doing enriched air nitrox diving is to use scuba with premixed gas. This is the method of choice for scientific and recreational diving. At least two methods are in use for preparing these mixtures. The simplest one involves filling oxygen-clean scuba cylinders to an appropriate pressure with oxygen and pressurizing to the full pressure with oil-free air, then checking with an analyzer after mixing and adjusting if necessary. A rig for this method is shown in Figure 5 (Dinsmore, 1989). The proportions can be determined using the gas laws and an accurate pressure gauge, or can be done by weighing the cylinder as each component is added. In all cases, analysis for oxygen content in the final mix is essential.

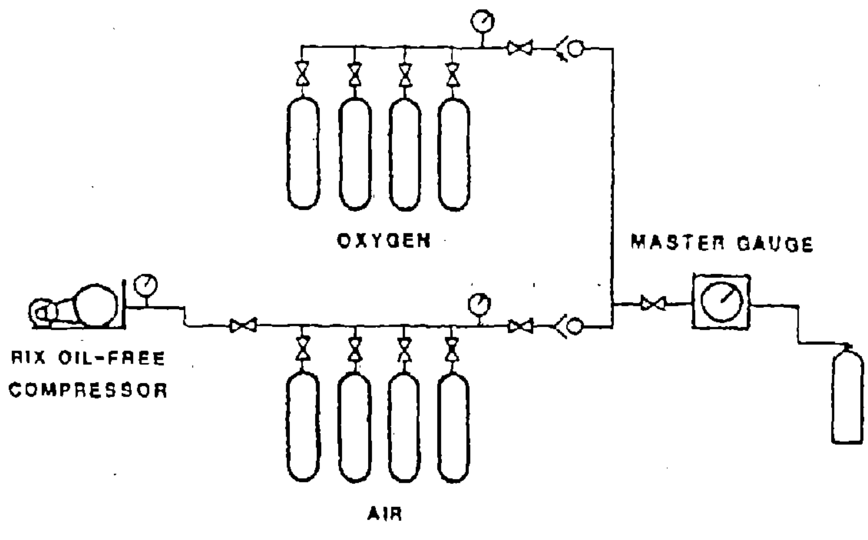


Figure 5. NURP / UNCW nitrox mixing system.

With this method it is necessary to allow the cylinder to mix before analyzing it. Mixing can be hastened by several methods, including rolling the tanks, heating them with a heat lamp or sunshine, or installing a perforated mixing tube inside the tank. Once mixed a gas mix will not separate, but if it is somehow allowed to become layered on mixing and allowed to stand still in a cold place it can take weeks to mix by diffusion (this problem is worse with heliox than nitrox mixtures). If a mix is high in oxygen it can be corrected by draining a small amount of mix and replacing with air; since only the air fraction can be compressed to full pressure (unless an oxygen-compatible compressor is used) to correct a mix too low in oxygen it will be necessary to reduce the pressure to below that of the oxygen supply cylinder in order to add more, then more air can to be added. A more sophisticated mixing method is to use a "blender" to feed an oil-free compressor which then fills the tanks or a storage bank. This can be done with one of the "on-line" blenders mentioned later in this chapter, or with a relatively simple blender that can be constructed from standard parts. The idea is to mix oxygen with air being fed to the intake of the compressor, check the analysis and adjust flows until it is right, then fill the cylinder with the compressor. It is not necessary to mix the gas in the cylinders after filling but they of course have to be checked with an analyzer. One such rig is shown in Figure 6 (Wells, 1989).

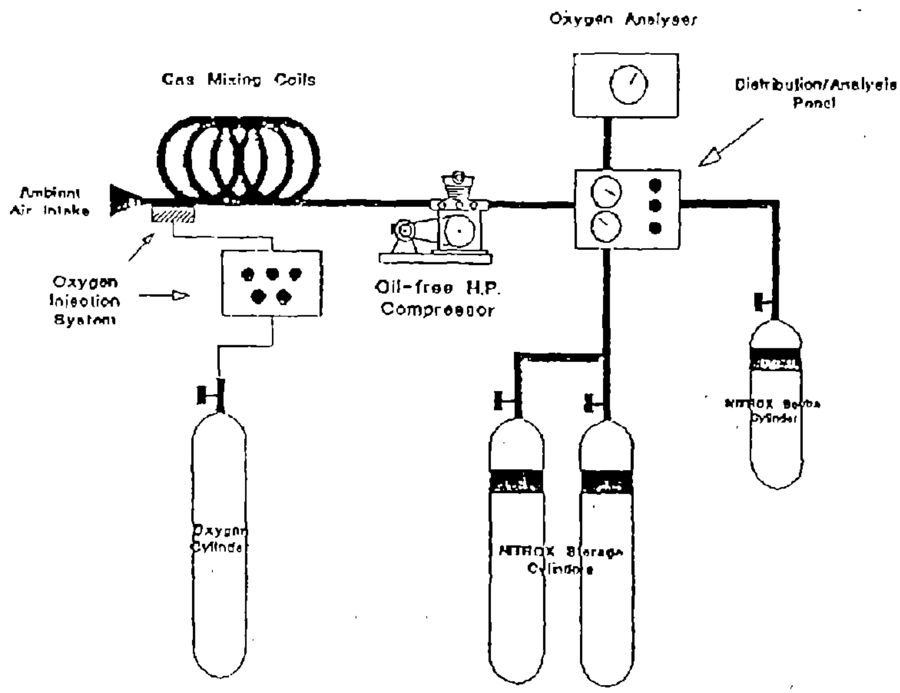


Figure 6. Gas blender mixing air and oxygen before compression.

In both approaches it is important to handle both oxygen and the enriched mixtures according to the rules for handling oxygen. Failure to do so can lead to fire and/or explosion. It is standard practice and highly recommended that the diver check each tank personally with an oxygen analyzer just before use. One benefit of mixing air with oxygen is that hypoxic mixtures are not possible; that would be a significant added risk if pure nitrogen were used as a source gas. It is important to start with an empty cylinder or make allowance for the mix inside it to begin with.

There is of course always the option to purchase premixed gases from the supplier. For many jobs this will be the most cost-effective solution.

2. *On-line mixing using gas blenders*

The most appropriate method for preparing nitrox gas mixes for commercial diving is by use of an on-line "blender." These devices are fed with compressed oxygen and oil-free air and provide an output mixture at sufficient pressure and flow to support one or more divers. Normally the oxygen content can be adjusted for the desired oxygen mix or for a choice of fixed mixes; ideally the blender would sense the diver's depth and supply the most efficient mix. The most common type of blender uses precision, pressure-compensated regulators and flow valves to prepare the mix. It usually goes into a mixing chamber where it is analyzed before being fed to the diver's hose. Mixers usually have alarms for oxygen level and gas pressures, and most systems have a bank of gas connected to the diver supply and set at a slightly lower pressure than the blender output so that it will take over and gas flow will not be interrupted in the event of blender failure.

The AGA blender, now Interspiro (Lidingö, Sweden) has been mentioned earlier in regard to nitrox use in Sweden, and the Dräger Polycom (Lübeck, West Germany) has been used for the major Norwegian jobs. (These two units are described in Appendix B) There have been units available in the U.S. made by Airco and McDermott, for example, but the availability of these from a supplier is doubtful due the difficult economic status of the U.S. diving industry. Several new "custom" blender designs are offered by Reimers Engineering in Alexandria, Virgina, USA.

There is another type of gas management system that might offer an attractive option to the blender. This is the membrane separator. By using selected polymer membranes it is possible to separate gases according to their individual properties by means of pressure alone. With such a unit it is not necessary to have oxygen on site, the mixes are made by essentially filtering out some of the nitrogen. One unit available for enriched air nitrox use is made by Krasberg (Aberdeen, Scotland); the "Air Splitter" will make mixes as rich as 42% oxygen on a single pass. These units are extremely reliable, with the compressor the only moving part, and they have the advantage that they can be turned around and used for "unriched" oxygen mixtures for nitrox saturation diving.

3. *Diver-worn rebreathers*

Historically the most common use of enriched air mixtures has probably been in with closed or semi-closed rebreather sets. This is almost exclusively a military practice, and since any details will depend on the nature of the specific rebreather this method is not covered here. One problem with rebreathers is that they rarely give a constant fraction of oxygen, usually a varying fraction or a constant partial pressure; this of course depends on the mechanism. This may require adjustment of the decompression table or procedure to match the oxygen behavior of the rebreather (Nishi, 1989).

B. Breathing equipment

Any general type of diver's breathing equipment that is operationally suitable and that can be used to deliver the desired gas mixture can be used for nitrox diving. The choice will normally depend on the source of the nitrox mix. For premixed gas usually the divers breathe by demand regulator and mouthpiece or mask. For the blenders the most common usage seems to have been with traditional "hard hat" gear using free flow. Demand regulators are also used with blenders. Breathing apparatus is an integral part of rebreather units.

C. Handling oxygen

Whatever the source, mixes with oxygen fractions higher than that of air are considered oxygen rich mixtures and are generally handled as oxygen. This can pose some design and fabrication limitations, depending on how the diving operation is regulated. In any case standard oxygen safety practices are mandatory. These should be routine for a modern diving organization. One important factor is that a compressor working with enriched air will have to be oil free and compatible with the mixes being pumped. The operator cannot do much about how a compressor is built except to select the correct one for the job, and to be sure that the piping and other fixtures are suitable for oxygen service and are cleaned before use. For systems that only pump air, it is critical that the compressor output air be oil free, either by design (e.g., teflon rings or seals) or by proper filtration. A dependable oxygen analyzer is essential. Even if "certified" mixes are purchased, it is still strongly advised that breathing gases be checked with an analyzer at the worksite for the proper oxygen content. Most experienced divers do this themselves. The oxygen analyzers using fuel cells or electrochemical cells are usually the best for field use, but paramagnetic analyzers may offer greater precision. For checking gas in cylinders or a gas stream it may be necessary to make a "cuvette" or small sampling chamber to ensure that the sensor is completely immersed in the gas to be measured, and that there are no undesired pressure effects at the measurement site. Nothing special is necessary, but sound gas analysis techniques should be used.

PART TWO. **BIOMEDICAL EVALUATION OF 7 DAYS OF ENRICHED AIR NITROX DIVING**

I. INTRODUCTION

As is pointed out in Part One, oxygen-enriched air or "nitrox" diving techniques allow more efficient and reliable decompression for dives in the range 9 to about 40 msw. They involve use of breathing mixtures for divers that have a higher fraction of oxygen than air, which hereby reduces decompression time. The consequence of higher oxygen levels is, however, of concern in mainly three areas: CNS toxicity, pulmonary toxicity, and other non-specified effects (Sterk, 1984; 1985). Also, although the formula used for determining the decompression time, the equivalent air depth (EAD), seems to work in practice and has theoretical advantages, there still is some skepticism about its validity.

A. *Rationale for performing the tests*

In order to accumulate more biomedical data from divers using nitrox the Swedish Naval Diving Center carried out a series of experimental chamber dives to add validation on both the reliability and safety aspects of nitrox diving. This part covers a series of simulated enriched air nitrox dives with extensive biomedical monitoring, with the objective of identifying any significant medical problems that may result from its use. The targets were oxygen exposure and decompression.

B. *Test considerations*

1. *Laboratory or field*

By using a "wet" laboratory chamber with standard operational equipment, experienced commercial divers, and tasks designed to be representative of routine work, dives could be carried out to the operational limit or slightly beyond and thus leave a margin of safety in the validation. The laboratory chamber also allowed the quality control and biomedical surveillance we felt was necessary, especially for the more subtle oxygen effects.

2. *Maximum PO_2 during a dive*

For CNS toxicity reasons PO_2 in operational nitrox diving is seldom above 150 kPa.This level affords a considerable range of diving within the method, yet is believed to almost completely eliminate the risk of CNS toxicity.

3. *Maximum daily oxygen dose*

Daily oxygen doses are less clearly established. However, the literature is relatively clear on the point that the tolerable dose is a function of the number of days of exposure. Therefore we felt it was important to choose a dose related to the duration of the dive series.

For the daily oxygen exposure limit we used the empirical Repex oxygen management algorithm (Hamilton, Kenyon, et al, 1988). This method sets the daily oxygen dose limit in Oxygen Tolerance Units (OTU) as a function of the overall duration of the exposure.

4. Overall exposure duration

We wanted the exposure to cover the maximum number of days that might be performed in consecutive commercial diving in Sweden, without a break. This we decided would normally be a 5-day work week, but that special considerations might lengthen this on occasion. We felt it to be quite unlikely that a diver would work steadily for more than 7 consecutive days.

5. Decompression stress

Although a wide range of dives will no doubt be done, diving in the nitrox range will be more convenient and operationally easier if dives can be made "no-stop" or with a direct ascent from the bottom, and most commercial dives are done in this manner. Many operators or divers will prefer to do it this way if possible. We therefore wanted to test dives of this sort, but felt it necessary also to test the decompression procedures used to the maximum allowable limit each day during the test period.

For decompression we chose the computational criteria of the new "Swen-88" air decompression tables under development by the Swedish Defence Research Establishment, Naval Medicine Division (Hamilton, Muren, et al, 1988).

6. CO_2 load

CNS oxygen toxicity is particularly sensitive to the body level of CO_2. This in turn is strongly affected by the work load performed by the diver and the type of breathing equipment used. We elected to have the divers stay busy constantly during the bottom time, which would be entirely in water. The underwater tasks would be typical of what they would do at work, and the work level we arbitrarily set so as to produce a heart rate 20 % above resting for about 50 % of the bottom time. For breathing equipment we felt only equipment in current use would be appropriate.

7. Divers

To be a valid representation of the typical diving work pattern it is also important that the divers be representative. Because the tests are pertinent to occupational medicine, it was felt they should be performed on currently active commercial divers. This was possible because of the collaboration of the Swedish commercial diving contractors organization.

8. Synopsis of test schedule

To get a cumulative oxygen dose slightly higher than the Repex proposed limit over a 7-day period, to test the decompression procedures to the limit, and to have time to do two dives in one day (in order to optimize topside and investigator resources) we used a 50/50 oxygen-nitrogen mix at 21 msw for a no-stop dive of 220 min each day.

C. *Medical evaluation and monitoring*

Medical monitoring was to be concentrated on the lungs and respiratory system, the heart and circulatory system, and the brain and nervous system, concentrating particularly on parameters that might reflect sensitivity to oxygen. For practical and budgetary reasons these had to be limited to simple measurements that could be made at the time of the dives and standard hospital tests that could be performed before and after each dive series.

II. METHODS

A. *The dive series*

Two 7-day dive series were carried out (Dec 88 and Feb 89) in the pressure chamber complex at MDC, the Swedish Navy Diving Center. There were 2 two-man teams of divers each week. The morning team was in the water from 0700 to 1045, and the afternoon team was in the water from 1300 to 1645. This gave us a total of 56 man-dives. Each diver did a 220 min wet dive at a simulated depth of 21 msw breathing 50/50 nitrox each day for 7 days.

B. *The divers*

Divers were active commercial divers that met the health qualifications for a commercial diver in Sweden. They ranged in age from 22 to 45 years and were of average build. The divers agreed to abstain from smoking, alcohol, and exhaustive physical exercise during the test period. This began one day before the first medical exam (two days before the first dive) and ended after the last exam had been approved the day after the last dive. All divers were "informed" volunteers in the test, and they received their normal salary during the test period. A summary of the divers is given in Table 7.

Table 7.
Divers

Diver no	Age	Height	Weight	Team
Group I				
1	45 years	180 cm	88 kg	Morning
2	40 years	186 cm	81 kg	Afternoon
3	40 years	174 cm	78 kg	Afternoon
4	22 years	186 cm	85 kg	Morning
Group II				
5	27 years	170 cm	75 kg	Morning
6	29 years	182 cm	76 kg	Morning
7	36 years	182 cm	98 kg	Afternoon
8	34 years	180 cm	92 kg	Afternoon

C. *Diver environment*

1. *Breathing equipment*

Two types of gas supply and breathing rigs were used. During the first series all four divers used standard "hard hats" modified for improved internal ventilation giving lower inspiratory CO_2. The second series was performed with Interspiro (née AGA) full face demand masks.

2. Breathing gas

Gas was mixed on line from air and oxygen either by a Dräger Polycom 101 or a prototype Interspiro (AGA) blender (see Part One, Sec. 5.A.2, and Appendix B). The oxygen fraction was typically between 0.49 and 0.51 as measured by in line paramagnetic analysis. Breathing gas was also sampled in front of the mouth of the diver to a Centronics mass-spectrometer. The mixed gas CO_2 level averaged about 1 kPa in the hard hats. In the demand mask mean inspiratory CO_2 level was lower, coming only from the inhalation mask dead-space.

3. Temperature

Water temperature ranged between 4 and 8^0 C. Dry suits were used in both series, with adequate wooly underwear.

4. Oxygen exposure

The overall oxygen exposure gave 413 OTU/day and a total of 2891 units at the end of 7 days, an entirely appropriate test value where the Repex dose is 2660. How this exposure fits the limits given in Figure 4, Part One, is shown in Figure 7.

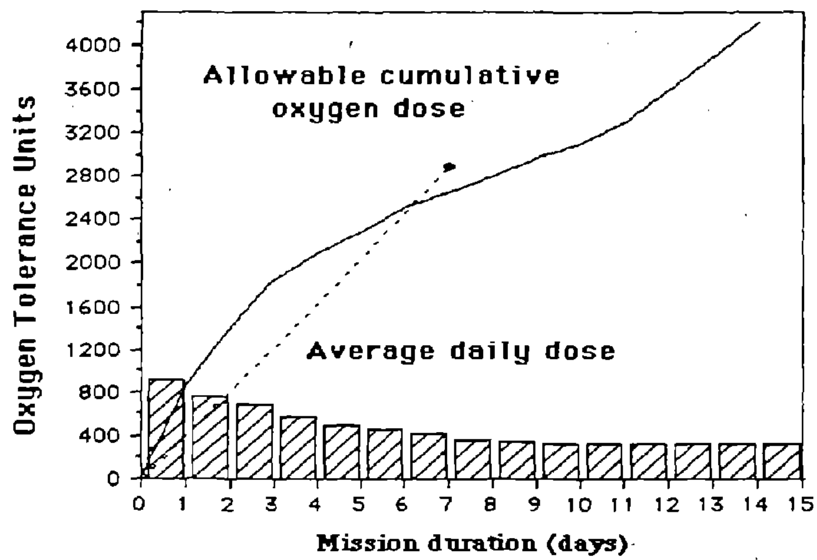


Figure 7. OTU doses on Repex curve. The curve is the value determined empirically to be an acceptable exposure, on the average. The dot shows the calculated exposure of each diver over 7 days. The Repex limit is exceeded slightly during the 7th day.

D. <u>Daily and in-dive monitoring</u>

1. Pulmonary function

Spirometry was done daily at MDC with an Ohio rolling seal spirometer. This included two FEV (forced expiratory volume) and two FIV (forced inspiratory volume) measurements about 1/2 h before each dive and 15 min after.

2. Interviews and questionnaires

Divers were examined and questioned by a physician-investigator, and they completed a general questionnaire before and after each dive. They were asked specifically about symptoms typical of oxygen exposure and decompression sickness.

3. Doppler bubble detection

Precordial ultrasound doppler signals were recorded 15, 75, and 135 min after surfacing, using a Parks model 614 tuned at 2.25 MHz and recorded on a Fostex Multitracker X-30. Ratings were taken at rest with the subject standing, then again after a deep knee bend. Bubble grades were determined using the KM code (Kisman et al, 1978).

E. Medical exam pre/post dive series

A pre-dive medical exam at the Karolinska Hospital was done 2 days before each series, and the post-dive exam was the day after the last dive. These exams included exercise capacity, pulmonary function, neurology, hematology, and blood chemistry.

1. Exercise test

The divers did an exercise test on an electrically braked bicycle ergonometer (Siemens-Elema EM 380B). The work rate was increased in 4 min, 50 W steps until exhaustion. A single ECG tracing was used to determine heart rate, blood pressure was taken by auscultation, and breathing frequency was counted. Heart rate, blood pressure, and arterial blood were taken at rest and at 100, 150, 200 W of workload, and a few seconds before the end of the test another blood sample was drawn for acid-base and lactate determinations. Blood was drawn through a thin teflon catheter in a brachial artery. Blood gases were done on a Radiometer ABL 3, and lactate concentration on an LKB Ratio Fluorometer .

Maximum O_2 uptake was estimated according to Åstrand and Rhyming (1954), corrected for heart rate.

2. Pulmonary function

Static spirometry (Sensor Medics 2400) included vital capacity (VC), total lung capacity (TLC), residual volume (RV), functional residual capacity (FRC), expiratory reserve volume (ERV), inspiratory capacity (IC), and tidal volume (V_t) Dynamic spirometry included forced vital capacity (FVC), forced expiratory volume in 1 sec ($FEV_{1.0}$), FEV %, and maximal expiratory flow (MEF at 75, 50, and 25 % of FVC), peak expiratory flow (PEF), and maximum voluntary ventilation at 40 breaths/min (MVV_{40}). Subjective fatigue was estimated by the divers against a Borg RPE scale 6-20 (Borg, 1982). Static compliance and maximal inspiratory lung elastic recoil pressure was determined using oesophageal balloons (Milic-Emili, et al, 1964).

3. Pulmonary diffusion capacity

Diffusion capacity for carbon monoxide (DLCO) was determined by the single breath test using a gas mixture of 10 % He, 21 % O_2, 0.3 % CO, balance N_2 (Salorine, 1976).

4. Neurology

Neurological tests included conduction velocity and distal latency of sensory and motor nerves, measured bilaterally in the median and ulnar nerves by neurography (ENeG). A clinical neurological exam performed by a neurologist included cognitive, psychological, motor, reflex, sensibility, and cranial nerve function.

5. Hematology

Blood tests including hemoglobin, erythrocyte partial concentration, erythrocyte volume fraction, and leukocytes were assayed with a Coulter Stacker. Electrolytes; sodium, potassium, and calcium, and enzymes glutamic oxaloacetic transaminase, glutamic pyruvate transaminase, and serum iron were measured with a Kodak Ektachem 700. Reticulocytes were counted manually by microscope.

6. Additional tests for which results are not available

A measurement of the divers sensitivity to CO_2 was performed before and after each series of dives, blood was sampled for erythropoietin, and urine was collected for later analysis of metabolites of prostaglandins and stress hormones. These results were to be analyzed by invited scientists, but results have not yet been obtained.

III RESULTS

A *Daily in house measurements*

1 *Questionnaires*

The daily medical exams and interviews and the questionnaires showed only minor problems as shown in Table 8.

Table 8

Diver No	Type of rig	Comments
1	H	Has some coughing all week. Does not get worse during dives. Feels slight dyspnea after some of the dives. No decrement of $FEV_{1.0}$ or peak flow. After day 6 mild tingling of toes. After the dive series less presbyopia than pre-dive.(This is normalized within a week post dive. Interpreted as training due to work in confined space)
2	H	Develops mild upper airway infection with stuffed nose and head ache during the series. No fever or pulmonary symptoms.Diving does not affect the symptoms.
3	H	-
4	H	-
5	D	-
6	D	-
7	D	Subjective tunnel vision a short period post dive day 5.
8	D (H)	Ear squeeze day 2. Dives with hard hat day 3 and 4.

H = hard hat D = demand full face mask

2 *Doppler*

Doppler scores showed 34 % of dives to be bubble free; several divers had Grade 1 or grade 2 bubbles occasionally, and there were a few 3-s but only after flexing which is looked upon as acceptable.

The bubble grades (score at rest/maximal score after knee-bend) and the heart rate (HR in beats/min) observed in every diver during the series of dives are compiled in Table 9.

Group I : Two of the divers (divers no 1 and 2) have almost no or few bubbles during the 7 days of diving.

The diver no 4 had very large variations of the bubble grades detected. He had 4 dives with almost no bubbles and 3 dives with a maximal bubble grade of 3 after knee-bends. These dives were the 3rd, the 6th and the 7th day.

For diver no 3, the bubble grades recorded after the decompression seemed to become progressively higher. During the first two dives, there were almost no bubbles. After the 3rd dive some bubbles were recorded and after the 4th, 5th and 6th dives bubble grades up to score 3+ after knee-bends were recorded. At the 7th dive, the bubble grades were a little less but still at 2+.

Table 9
Bubble scores (K-M) (resting / flexing) and HR in divers 15, 75, and 135 min post direct ascent after a 220 min dive at 21 msw using 50% nitrox.

GROUP I	diver	1		2		3		4	
		bubble	HR	bubble	HR	bubble	HR	bubble	HR
day	t(min)								
881130	15	0/0	100	0/0	88	0/0	92	0/0	92
	75	0/0	92	0/0	88	0/0	120	0/1	100
	135	0/1-	84	0/0	100	-	-	-	-
881201	15	0/0	100	0/0	84	0/0	88	0/1-	88
	75	0/0	100	1-/1-	96	0/0	100	1/1	120
	135	0/0	88	1/1	110	-	-	-	-
881202	15	1/3	120	0/1-	80	1-/1-	88	1-/1	84
	75	2+/3	80	1-/1	92	1/2-	80	0/2	68
	135	1/3	96	0/1	96	-	-	-	-
881203	15	0/0	92	0/1-	84	0/0	72	1/2	80
	75	0/1	92	1/1	88	0/1-	92	2/3	92
	135	0/0	78	-	-	-	-	1/2	104
881204	15	0/0	100	0/0	80	0/0	76	2/2+	72
	75	1-/1	100	1/1	84	1/1-	100	2+/3-	104
	135	-	-	1-/1	100	-	-	1/2+	100
881205	15	2/3-	112	0/0	84	1/2-	84	2/3	80
	75	2+/3	100	0/1	92	1/2	84	2/3-	84
	135	2+/3-	92	0/1	108	0/1+	88	1+/2+	84
881206	15	1-/1	108	0/1-	76	1/1-	88	1-/1	76
	75	2+/3	88	1-/1	96	1/1+	120	2/2+	96
	135	0/2	96	-	-	-	-	1/2+	96
GROUP II	diver	5		6		7		8	
		bubble	HR	bubble	HR	bubble	HR	bubble	HR
890201	15	0/0	68	0/0	72	1/3	68	1-/1	88
	75	0/0	96	0/0	96	2/3+	76	0/0	96
	135	-	-	-	-	2/2+	80	-	-
890202	15	0/0	64	0/0	80	0/0	72	0/0	76
	75	0/0	80	0/0	88	1/2	72	0/1	92
	135	-	-	-	-	1-/2+	72	-	-
890203	15	0/0	76	0/0	84	1/1	76	0/1-	88
	75	0/0	88	0/0	96	1-/1	80	0/1	88
	135	-	-	-	-	1-/1+	72	-	-
890204	15	0/0	76	0/0	84	0/0	68	0/0	90
	75	0/0	96	0/0	88	1-/1	80	0/0	92
	135	-	-	-	-	0/1-	76	-	-
890205	15	0/0	72	0/1-	76	0/0	64	0/1+	96
	75	0/0	92	0/2-	96	0/1+	72	1-/1+	108
	135	-	-	0/1+	96	-	-	-	-
890206	15	1-/0	68	0/0	76	1-/1	72	1/1+	88
	75	1/1	96	0/0	116	2-/2+	68	1/2-	92
	135	1-/1+	124	-	-	1+/2+	80	0/1-	100
890207	15	0/1-	72	0/0	84	0/1-	76	0/0	84
	75	0/0	112	0/0	112	1/2	88	1-/1-	90
	135	-	-	-	-	1/1-	96	-	-

Group II : Very low bubble grades (≤2) were recorded in this group except for the diver no 7 at two occasions where the maximal bubble scores after knee-bends were 2+ and 3+.

The HR recorded are often > 80 beats/min. Divers were examined right after doffing the hard hat equipment and after a meal.

3 *Spirometry*

The results of daily pre-dive $FEV_{1.0}$ performed at the laboratory, just before entering the chamber, are displayed in Fig 8. No significant difference was found pre/post dive measurements each day.

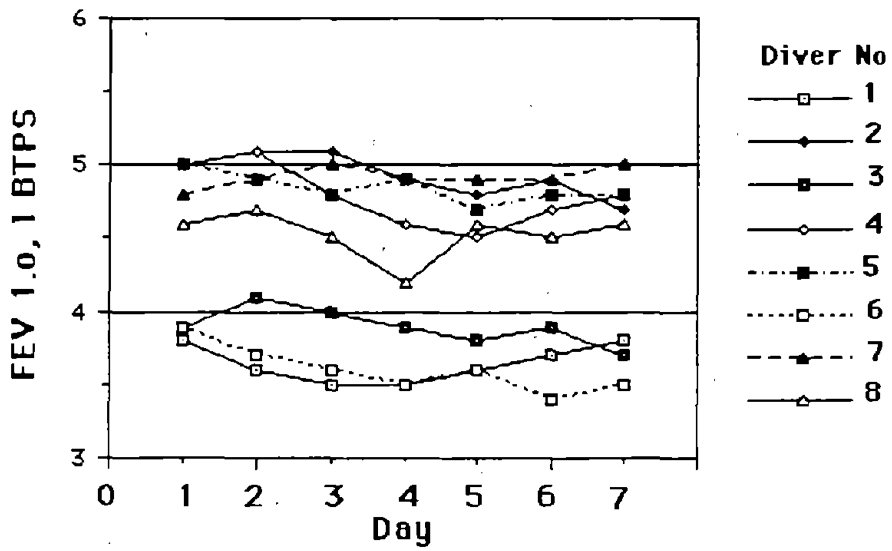


Figure 8. Forced expiratory volume ($F\dot{E}V_{1.0}$) performed daily before 21 msw/220 min wet chamber dives at a PO_2 of 155 kPa over 7 days.

B *Hospital measurements pre/post dive series*

The results from the hospital pre- and post-dive series tests are displayed in Figs 9 - 12. Paired t-test analyses of pre- and post-dive data gave statistical significant differences as shown by * = $p< 0.05$ ** = $p< 0.01$. Of physiological importance are only the reduction of $MEF_{25\%}$ and maybe the decrease of reticulocytes. In Appendix A are all individual changes plus mean values before and after the series depicted. In these graphs are normal or reference values shown by shaded areas, and significance levels from paired analysis pre post are given above the group means. Because of the possible impact of oxygen on the gas flow in smaller airways a detailed analysis of individual values regarding expiratory flow is also enclosed in Appendix A.

1. Pulmonary function

The $MEF_{25\%}$ decreased from 2.28 liter/s pre-dive to 1.79 liter/s post-dive series. None of the other pulmonary function tests showed any significant changes, but there were tendencies in $MEF_{75\%}$, $MEF_{50\%}$, FEV, $FEV_{1.0}$/ FEV, PEF and MVV_{40} to be lower post series in some divers. Pulmonary diffusion capacity was down slightly in 5 of 7 divers, but the variability prevented this from being statistically significant.

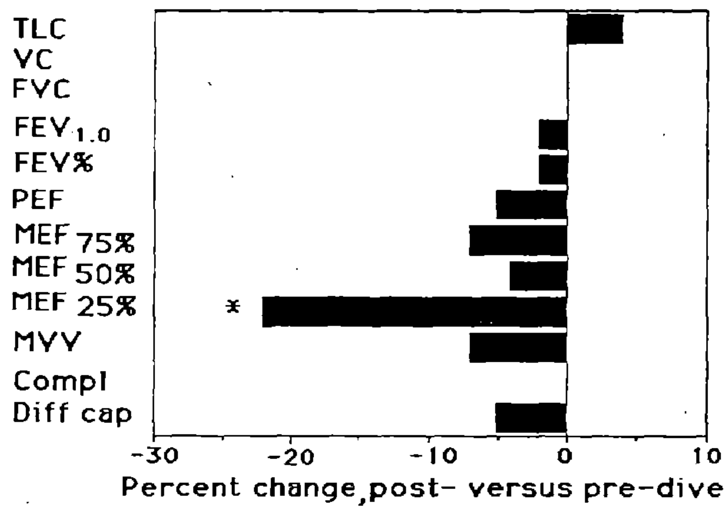


Figure 9. Percent change in mean values for spirometry data from 8 divers pre-post a 7 day series of daily wet chamber dives to 21 msw/220 min at a PO_2 of 155 kPa .(* = $p<0.05$.) For abbreviations see Methods.

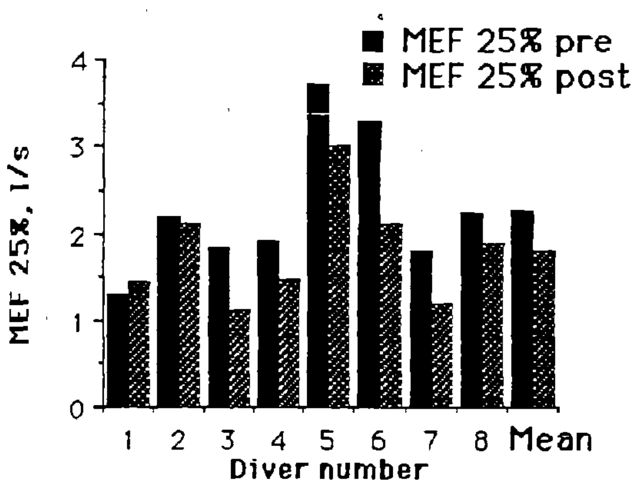


Figure 10. Maximum expiratory flow at 25% FVC, before and after a 7 day series of daily wet chamber dives to 21 msw/220 min at a PO_2 of 155 kPa

2. Exercise test

As seen in Fig 11, the pre- and post-series exercise tolerance tests revealed no change in maximum performance level. However, some performance-related cardio-vascular variables showed "improvement". There was a slight but significant reduction in mean values for HR, decrease in systolic blood pressure, and increase in P_aO_2, all when measured at the 200 W exercise level, and a small but significant increase in calculated maximum O_2 uptake.

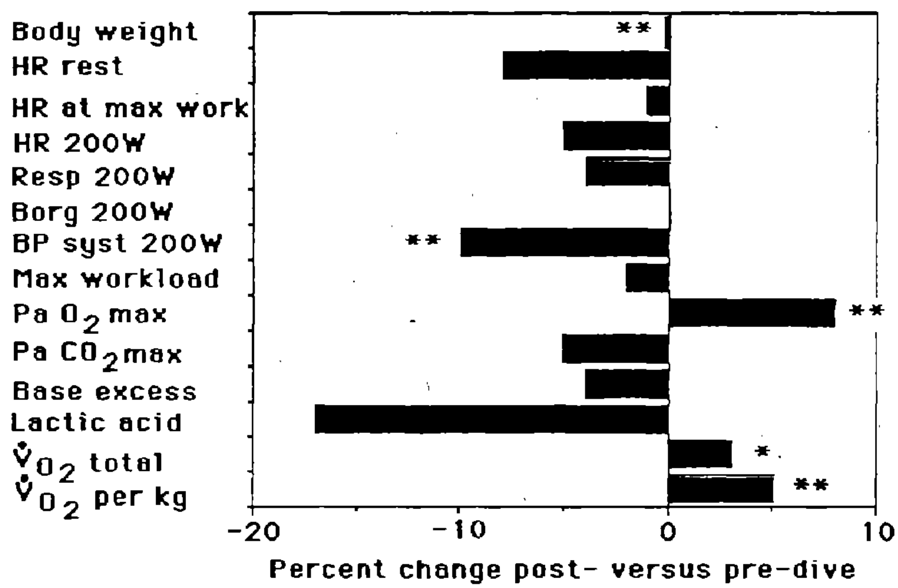


Figure 11. Percent change in mean values for ergomety data from 8 divers pre-post a 7 day series of daily wet chamber dives to 21 msw/220 min at a PO_2 of 155 kPa .(* = p<0.05; ** = p<0.01.) For abbreviations see Methods.

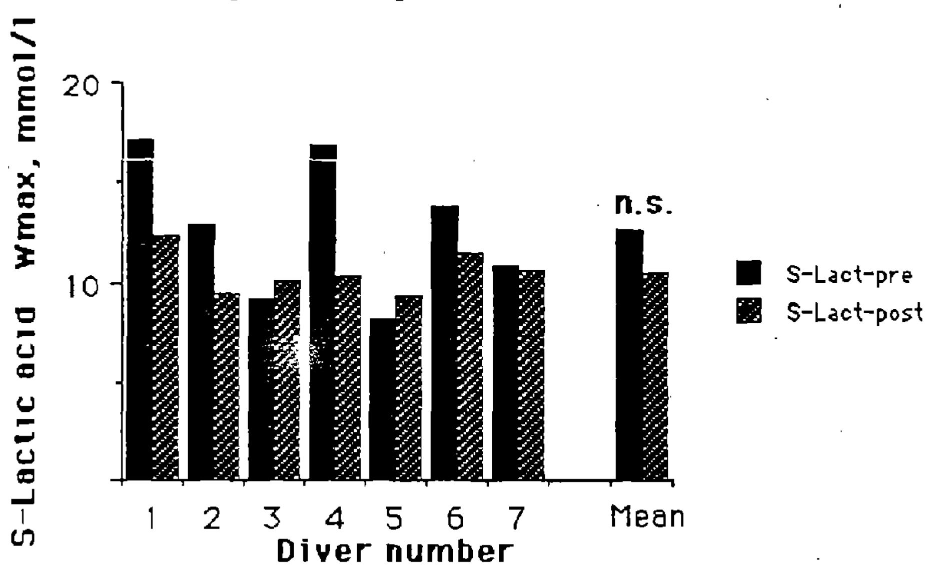


Figure 12. Arterial blood lactic acid levels at W_{max}, before and after a 7 day series of daily wet chamber dives to 21 msw/220 min at a PO_2 of 155 kPa.

As shown in Figure 13 the arterial blood lactate was down at all levels of exercise on the post series measurement and not only at maximum working capacity .

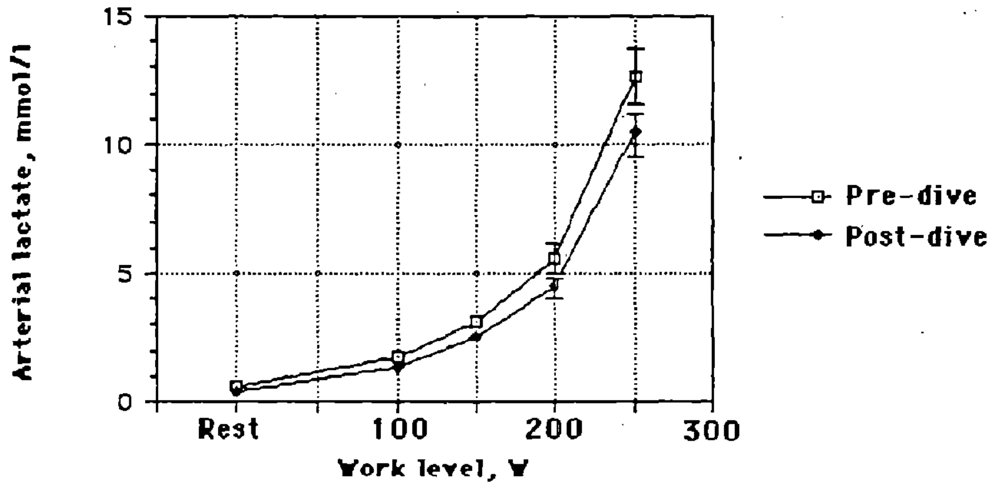


Figure 13. Mean arterial blood lactate of 7 divers at W_{max} pre- and post a 7 day series of daily wet chamber dives to 21 msw/220 min at a PO_2 of 155 kPa. (Bars indicate SD)

3. Neurology

Conduction velocities remained remarkably uniform over the series, and none of the other neurological evaluations showed changes of clinical importance.

4. Blood

Both hemoglobin and EVF (hematocrit) showed small but statistically significant drops over the series. Reticulocytes were down substantially after the oxygen exposure (1 % to 0.5 %). Other changes in blood were a drop in Na^+, Ca^{++} and leukocytes.

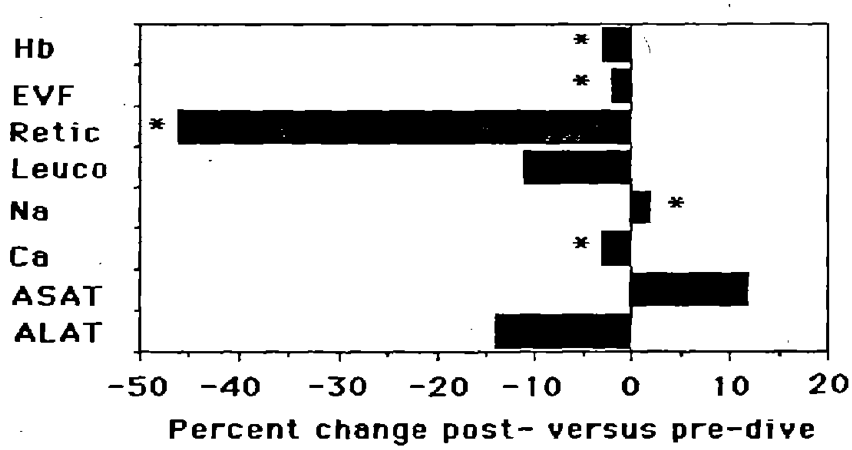


Figure 14. Percent change in mean values for blood data from 8 divers pre-post a 7 day series of daily wet chamber dives to 21 msw/220 min at a PO_2 of 155 kPa .(* = $p<0.05$) For abbreviations see Methods.

IV DISCUSSION

These results confirm one more time the large inter and intra individual differences of the physiology of humans. The bubble grades recorded with ultrasound doppler indicate the differences between humans in the way inert gas is eliminated during and after decompression. The doppler results were, however, consistent with the concept that the decompression procedures used are acceptable. These results do not show any evidence of general increase in the bubble scores with the number of dives performed although such a trend was observed in our diver. These dives involved more decompression stress than would be possible if similar dives were done using the "equivalent air depth" principle. It is unlikely that actual commercial activities would approach these limits. We regard these tests as further substantiation to the Swen 88 tables (Hamilton, 1988).

From this multi day exposure to elevated oxygen within or barely outside current tolerance limits we expected to see some slight symptoms of physiological "reaction" to oxygen, but few real symptoms. The daily pre- and post-dive spirometry might have been expected to show some effects on VC. According to the equation determined by Harabin and colleagues (1987), the drop for a single day exposure (413 OTU) would be -2.5 %. We saw no pattern of change, but the daily spirometry measurements included both FEV and FIV maneuvers, which might have masked the type of change in VC that may follow a period of hyperoxia.

One set of changes was in the exercise performance tests; all changes appeared to be toward a higher level of fitness after the dive series. This could possibly be a form of a "training effect" of a week of daily workout. In any case they are not in an unfavorable direction.

Although $FEV_{1.0}$ and FEV % were unaffected the $MEF_{25\%}$ was reduced. This reflects a change in small airway function. After one continuous exposure to 2 ata oxygen for more than 10 h Hendricks et al (1977) found more pronounced decreases in inspiratory flow rates than in expiratory. This was interpreted as an effect mainly on the inspiratory muscles. Kirsteen and coworkers (1972) demonstrated a 30 % increase in airway resistance after 2 ata oxygen for 5 h which they interpreted as an airway smooth muscle constriction of the same nature as the vascular constriction seen during hyperoxia. These authors concluded that this effect is reversible within a few h because other measurements, using longer delays between exposure and measurements, have not registered any increases in airway resistance. Further support to the notion that the change in airway resistance after oxygen exposure probably is only transitory is given by the study of Moselhi et al (1980) on 65 divers who had been exposed to 1 - 2 atm oxygen for 90 min twice weekly over 2 to 10 years without getting any significant decrease of $MEF_{25-75\%}$ in comparison to a control group who had not been exposed to oxygen.

The sharp reduction in reticulocytes is consistent with a halt in production of new red cells. This is certainly the expected effect, but the degree is more than we anticipated for this dose of oxygen. We had hoped to get a firmer handle on this by analysis for erythropoietin, but this analysis was not completed. One might wonder what longer exposures could have caused. However, if the Repex limits are followed, the total dose for 7 days would be lower (380 OTU/day rather than the 413 used here), and for a longer exposure the limit would be even lower. The drop in red cell indexes, small but statistically significant, is also consistent with acclimation to hyperoxia.

V CONCLUSION

The divers tolerated the exposures very well. Some changes were detected which came out as statistically significant, but these probably reflect acclimation to the elevated daily oxygen dose, or possibly to the regime itself. Nothing we observed appears to augur against approving the procedure.

VI RECOMMENDATIONS FOR THE FUTURE

In the conducted series of dives (56 man dives) no observations were made that would justify a more conservative approach than that suggested in part one which means use of Repex limits for oxygen exposure, and a maximum PO_2 of 155 kPa. However, for operational use it is recommended that a maximum PO_2 of 140 kPa is planned to allow for a safety margin in case of variation of the oxygen fraction in the gas from the mixer and/or in diver depth.

Regarding decompression, the SWEN 88 tables were used, which are more conservative than the currently approved DYK:RM. However, there is no strong evidence that the use of DYK:RM tables and equivalent air depth (EAD) should give an unacceptable high incidence of decompression sickness.

To further elucidate the acclimation to elevated oxygen partial pressures seen in our divers we recommend that divers, taking part in future operational nitrox dives involving more than 1500 OTU/week, if possible should be given special medical examinations in the form of blood and spirometry measurements before and after the work period. More than 2 such examinations should not be needed for each diver/year unless significant changes are observed. Such a routine should make it easier to accumulate data from a great number of divers to show if continuous nitrox diving could cause any occupational hazards. It should be of great help if all divers involved in nitrox diving could use a special log for their oxygen exposure in order to facilitate the interpretation of medical data and make it possible to correlate changes observed to the oxygen exposure.

Based on current knowledge a medical follow-up of nitrox divers should include:
a) dynamic spirometry with an analysis of MEF and MIF (75,50, and 25 %)
b) blood sample for determination of reticulocytes and erythropoietin.

Such a "minimum follow-up" of nitrox divers does not mean that all oxygen effects on humans are known. Further research should be encouraged, but since the expected changes are small it is maybe better to plan such experiments as pure laboratory experiments than to involve divers in operational diving because of the many other effects caused by diving.

REFERENCES

Åstrand PO, Ryming I. A nomogram for calculation of aerobic capacity from pulse rate during sub-maximal work. J Appl Physiol 7:218-221, 1954.

Arntzen AJ. Alternatives to standard air tables. In: Örnhagen HC, ed. Diving and hyperbaric medicine: Proceedings XIth Annual Meeting of EUBS. FOA Report C50021-H1.(ISSN 0347-7665) Stockholm: National Defense Research Establishment, 1985.

Arntzen AJ, Eidsvik S. Modified air and nitrox diving and treatment tables. NUI Report. 30-80. Bergen: Norwegian Underwater Inst., Sep 1980.

Bardin H, Lambertsen CJ. A quantitative method for calculating pulmonary toxicity. Use of the "Unit Pulmonary Toxicity Dose" (UPTD). Institute for Environmental Medicine Report.Philadelphia: University of Pennsylvania, 1970.

Berghage TE, McCracken TM. Equivalent air depth: Fact or fiction. Undersea Biomed Res 6(4):379-384, 1979 a.

Berghage TE, McCracken TM. Use of oxygen for optimizing decompression. Undersea Biomed Res 6(3):231-239, 1979 b.

Butler FK, Thalmann ED. Central nervous system oxygen toxicity in closed-circuit scuba divers II. Undersea Biomed Res 13(2):193-224, Jun 1986.

Butler FK, Thalmann ED. CNS oxygen toxicity in closed-circuit scuba divers. In: Bachrach AJ,Matzen MM, eds. Eighth Symposium on Underwater Physiology. Bethesda, MD: Undersea Medical Society, 1984.

Bøe I, Hartung KH. Employment of the Polycom 101 gas mixing unit for divers in a major project in Norway. Draeger Review 51:26-28, Apr 1983.

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

Clark JM. Oxygen toxicity. In: Bennett PB, Elliott DH, eds. The physiology and medicine of diving. Third ed. San Pedro, CA: Best, 1982.

Clark JM, Lambertsen CJ. Pulmonary oxygen toxicity: a review. Pharmacological Reviews.23(2):37-133, 1971.

Crosbie WA, Cumming G, Thomas IR. Acute oxygen toxicity in a saturation diver working in the North Sea. Undersea Biomed Res 9(4):315-319, Dec 1982.

Crosson DJ. The use of nitrox for support in scientific diving operations. Presented at 9th meeting of US-Japan Cooperative Program in Natural Resources (UJNR) meeting, Yokosuka,Japan, Nov 1987.

Crosson DJ. Nitrox diving in science. In: Diving for Science 1986. Costa Mesa, CA: American Academy of Underwater Sciences, 1986.

Eckenhoff RG, Dougherty JH, Messier AA, Osborne SF, Parker JW. Progression of and recovery from pulmonary oxygen toxicity in humans exposed to 5 ata air. Aviat Space Environ Med 58(7):658-67, 1987.

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

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

Galerne A, Butler GJ, Hamilton RW. Assessment of various shallow water diving techniques. In: Cox FE,ed. Proceedings 3rd Annual Canadian Ocean Technology Congress. Toronto: Underwater Canada, 1984.

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

Hamilton RW, Kenyon DJ, Peterson RE. Effects of duration of exposure to M-values on the validity. In: Berghage TE ed. Decompression Series. UMS Publ. 29WS(DT) 6/25/80. Bethesda, Md; UMS 1978.

Hamilton RW, Kenyon DJ, Peterson RE, Butler GJ, Beers DM. Repex: Development of repetitive excursions, surfacing techniques, and oxygen procedures for habitat diving. Technical Report 88-1A.Rockville, MD: NOAA Office of Undersea Research, May 1988.

Hamilton RW, Kenyon DJ, Peterson RE. Repex habitat diving procedures: Repetitive vertical excursions, oxygen limits, and surfacing techniques. Technical Report 88-1B. Rockville, MD: NOAA Office of Undersea Research, May 1988.

Hamilton RW, Muren A, Röckert H, Örnhagen H. Proposed new Swedish air decompression tables. In: Shields TG, ed. Proceedings XVth annual meeting of the EUBS. Aberdeen: National Hyperbaric Center, 1988.

Harabin AL, Homer LD, Weathersby PK, Flynn ET. An analysis of decrements in vital capacity as an index of pulmonary oxygen toxicity. J Appl Physiol 63(3):1130-5, 1987.

Harabin AL, LD Homer, PK Weathersby, ET Flynn. Predicting pulmonary O_2 toxicity: A new look at the unit pulmonary toxicity dose. Report 86-52. Bethesda, MD: Naval Medical Research Institute, Dec 1986.

Hartung KH. Use of gas mixers in shallow water diving. In: Seemann K, ed. Proceedings VIIIth annual congress of European Undersea Biomedical Society. Lübeck: Drägerwerk AG, 1982.

Hendricks PL, Hall DA, Hunter Jr WL, Haley PJ. Extension of pulmonary O_2 tolerance in man at 2 ATA by intermittent O_2 exposure. J Appl Physiol 42(4):593-599, 1977.

Hills BA. A cumulative oxygen toxicity index allowing for the regression of effects at low inspired oxygen partial pressures. Report. 4/76. London: Royal Navy Physiological Laboratory, 1976.

Hyacinthe R, Broussolle B. Effets pulmonaires au long cours de l'hyperoxie chez le nageur de combat. Med. Aeronautique Spatiale, Med. Subaquatique Hyperbare 18(72):322-324, 1979.

Imbert JP, Bontoux M. Proposition d'un manuel de procedures de decompression a l'air. Fiche No 4273. Final report to Centre d'Etudes Petrolieres et Marines. Marseille: Comex Services, 1987.

Kirsteen M, Dewar S, Smith G, Spence AA, Ledingham I McA. Effect of hyperoxia on airway resistance in man. J Appl Physiol,32(4):486-490, 1972.

Kisman KE, Masurel G, Guillerm R. Bubble evaluation code for ultrasonic decompression data. Undersea Biomed Res 5(1, Suppl):28, 1978.

Lambertsen CJ. Discussion after Dr. Hamilton. In: Hamilton RW, Hulbert AW, Crosson DJ, eds. Harbor Branch workshop on enriched air nitrox diving. Technical Report 89-1. Rockville, MD:NOAA Office of Undersea Research, 1989.

Lambertsen CJ. Effect of hyperoxia on organs and their tissues. In Robin E, ed., Extrapulmonary manifestations of respiratory disease. New York: Marcel Dekker, 1987; pp 239-303.

Leitch DR, Barnard EEP. Observations on no-stop and repetitive air and oxynitrogen diving. Undersea Biomed Res 9(2):113-129, 1982.

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

Miller JN. Pulmonary oxygen toxicity. In: Proc Joint SPUMS and Repub of Singapore Navy Underwater Medicine Conference. SPUMS J (Suppl):42-46, 1981.

Moselhi S, Abdallah SM, Azab YM. Pulmonary function in men with intermittent long-term exposure to hyperbaric oxygen. Undersea Biomed Res 7(2):149-157, 1980.

Muren, A. Nitrox diving with constant oxygen partial pressure. Försvarsmedicin 9:251-252, 1973.

Muren A. Nitroxdykningar med AGA blandare Sept-Nov 1971. Stockholm: Marinens Dykerikontor, April 1973. (Unpublished internal report.)

Muren A. Nitroxdykningar med AGA blandare 1970.10.06-29. Stockholm: Marinens Dykerikontor, 1970. (Unpublished internal report.)

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

NOAA diving manual, Miller JW, ed. Second edition. Rockville, MD: NOAA, U.S. Department of Commerce, 1979.

Overland T. Discussion by Terry Overland. In: Hamilton RW, Hulbert AW, Crosson DJ, eds. Harbor Branch workshop on enriched air nitrox diving. Technical Report 89-1. Rockville, MD:NOAA Office of Undersea Research, 1989.

Piantadosi CA, Clinton RL, and Thalmann ED. Prolonged oxygen exposures in immersed exercising divers at 25 fsw (1.76 ATA). Undersea Biomed Res. 6(4):347-356, 1979.

Rashbass C, Eaton WJ. The effect of oxygen concentration on the occurrence of decompression sickness. RNPL Report 10/57. Alverstoke, Hants, UK: AMTE Physiology Laboratory, 1957.

Renie C, Volturo F, Bianchini A, Di Marzio GE, Venuti P, Settimi F. Mathematical assumption to determine the UPTD elimination during a period of interval between HBO applications. In: Marroni A, Oriani B, eds. EUBS 87: Diving and hyperbaric medicine. Proceedings of the XIIIth annual meeting of the European Undersea Biomedical Society, Palermo, Italy. Published by the Society, 1987.

Rutkowski D. Discussion by Dick Rutkowski. In: Hamilton RW, Hulbert AW, Crosson DJ, eds. Harbor Branch workshop on enriched air nitrox diving. Technical Report 89-1. Rockville, MD:NOAA Office of Undersea Research, 1989.

Shilling CW, Werts MF, Schandlemeier NR, eds. The underwater handbook: A guide to physiology and performance for the engineer. New York: Plenum Press, 1976.

Sterk W, Schrier LM. Nitrox-Proeven oosterschelde 1984. Voorlopige resultaten. Vriens Diving Co. BV. Bergen op Zoom, The Netherlands. Oct 1984.

Sterk W, Schrier LM. Effects of intermittent exposure to hyperoxia in operational diving. In: Örnhagen H, ed. Proceedings XIth Annual Meeting of EUBS. FOA Report C50021-H1. Stockholm: National Defense Research Establishment, 1985. (ISSN 0347-7665)

Sterk W. Intermittent hyperoxia in operational diving: what are the safe limits? In: Schrier LM,de Jong MH, Sterk W, eds. Diving and hyperbaric medicine. Proceedings XIIth Annual Meeting of EUBS. Rotterdam: Foundation EUBS, The Netherlands, 1986.

Sterk W. The use of oxygen in decompression. In: Lanphier EH, Nashimoto I, eds. Workshop on decompression in surface-based diving. 73(DEC)6/15/87. Bethesda, MD: Undersea Hyperbaric Medical Soc, 1987.

Stillson GD. Report on deep diving tests, 1915. Cited in Cargyle EC. Report on deep diving tests--1915. Faceplate 1(1):5-9, 1988.

Swen-88 Diving Tables. Horsfjerden, Sweden: FOA and Navy Diving Center, in preparation, 1988.

Thalmann ED. Air-N_2O_2 decompression computer algorithm development. NEDU Report. 8-85. Panama City, FL: U.S. Navy Experimental Diving Unit, Aug 1986.

Thalmann ED. Phase II testing of decompression algorithms for use in the U.S. Navy underwater decompression computer. NEDU Report 1-84. Panama City, FL: US Navy Experimental Diving Unit, Jan 1984.

U.S. Navy Diving Manual. NAVSEA 0994-LP-001-9010. Volume 2. Rev.1. Washington: Navy Department, Jul 1981.

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

Weathersby PK, Hart BL, Flynn ET, Walker, WF. Human decompression trial in nitrogen-oxygen diving. NMRI 86-97. Bethesda, MD: Naval Medical Research Inst., Sep 1986.

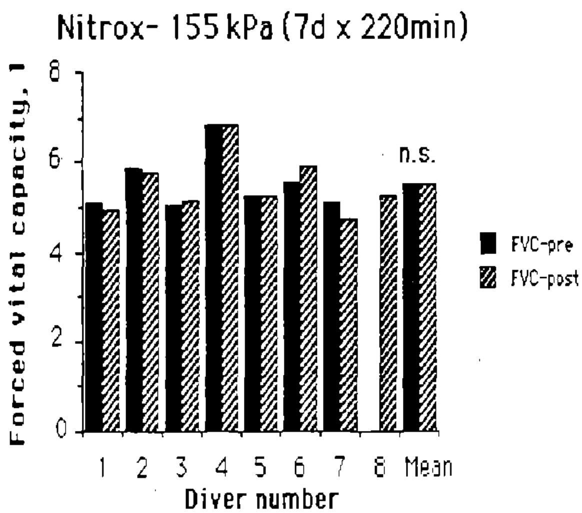
Weathersby PK, Hart BL, Flynn ET, Walker, WF. Role of oxygen in the production of human decompression sickness. J Appl Physiol 63(6):2380-7, 1987.

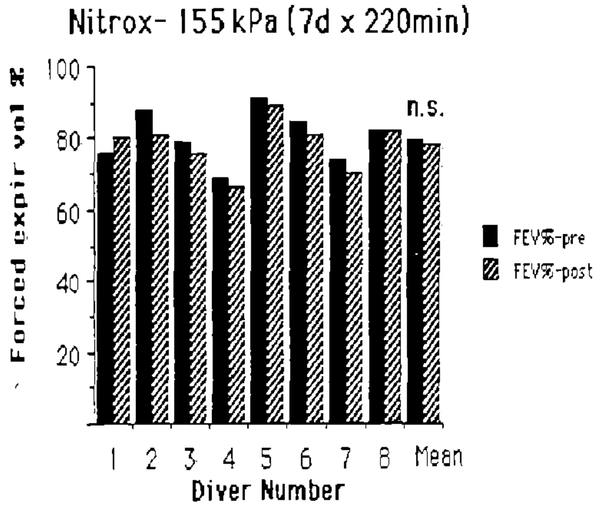
Wells JM. The use of nitrogen-oxygen mixtures as divers breathing gas. In: Hamilton RW,Hulbert AW, Crosson DJ, eds. Harbor Branch workshop on enriched air nitrox diving. Technical Report 89-1. Rockville, MD: NOAA Office of Undersea Research, 1989.

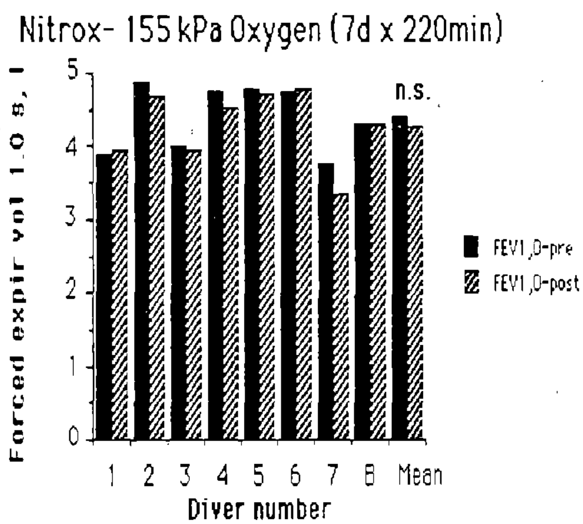
Wright WB. Use of the University of Pennsylvania, Institute for Environmental Medicine procedure for calculation of cumulative pulmonary oxygen toxicity. Report 2-72. Washington:U.S. Navy Experimental Diving Unit, 1972.

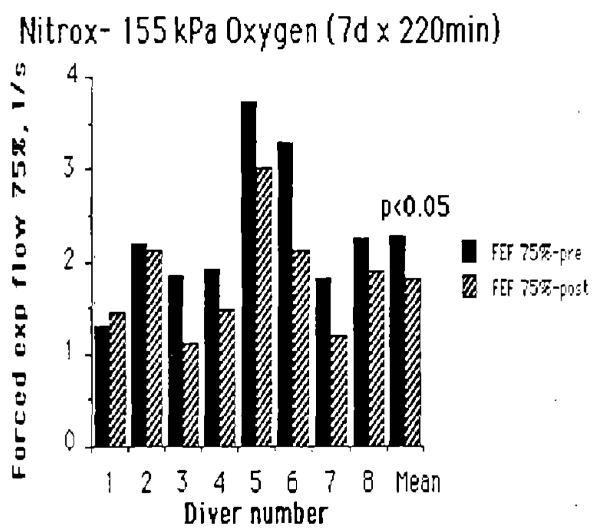
APPENDIX A

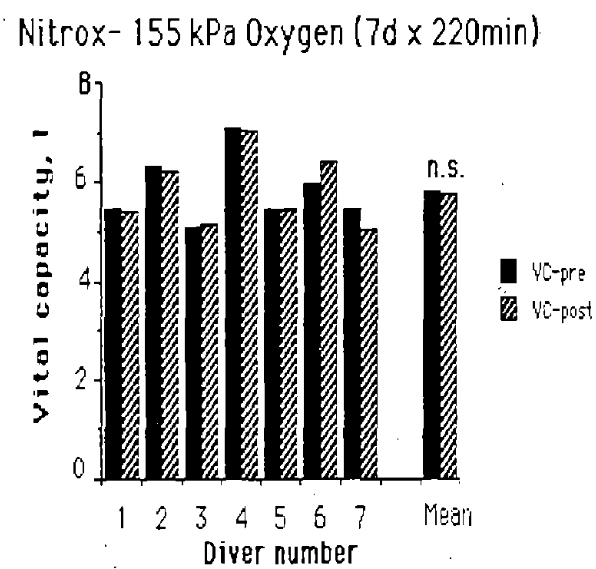
Spirometry data

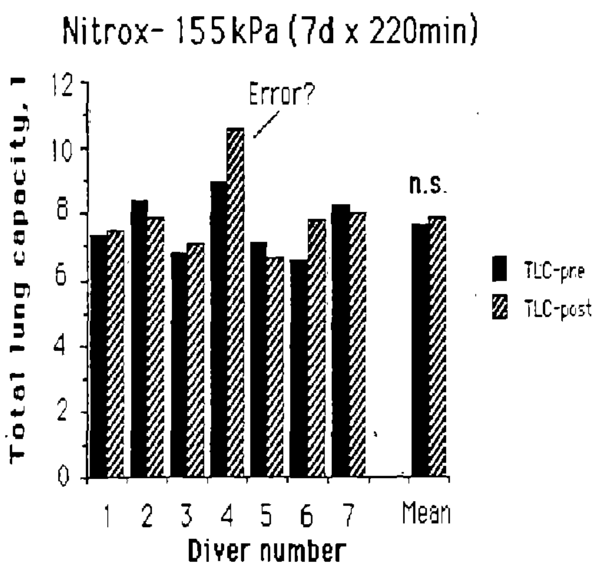






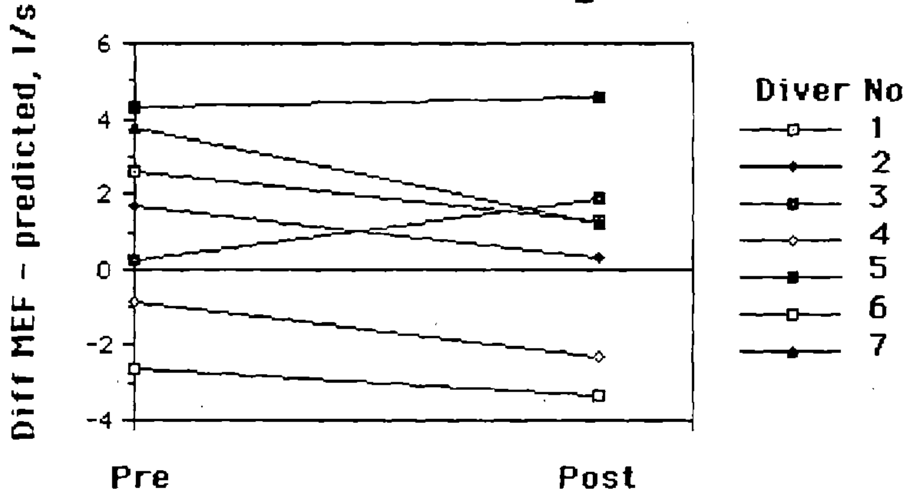




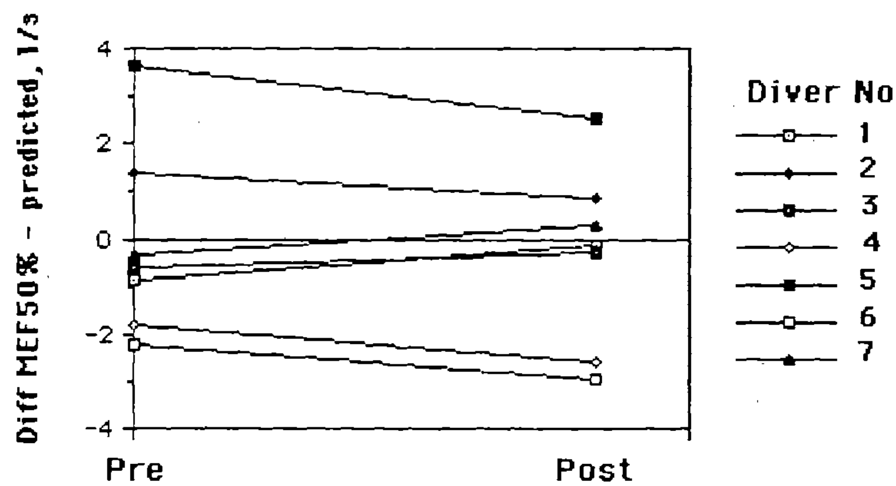


Preceding page blank

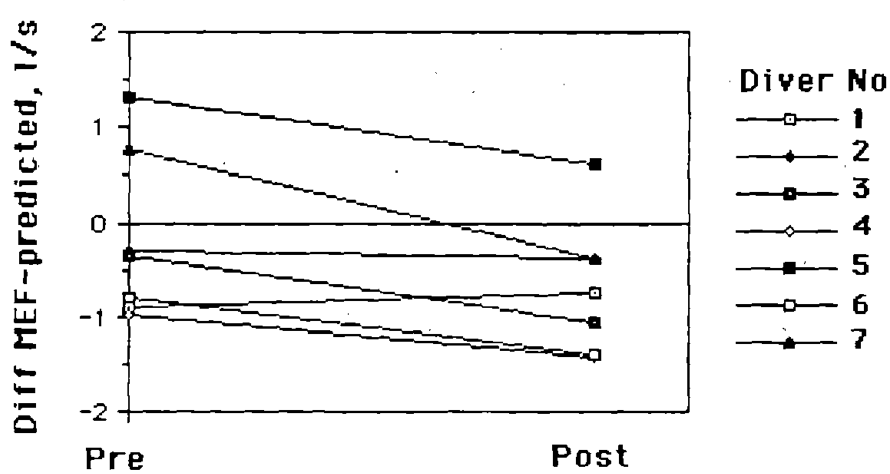
Difference Max Exp Flow 75% - predicted, pre - post nitrox 155kPa O_2 (7d x 220min)

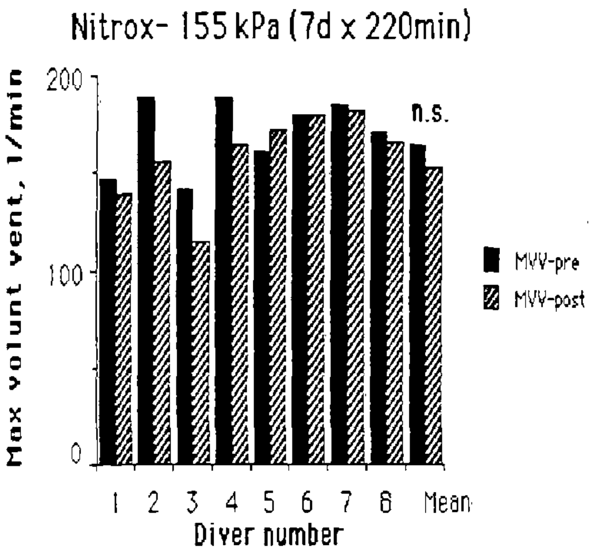


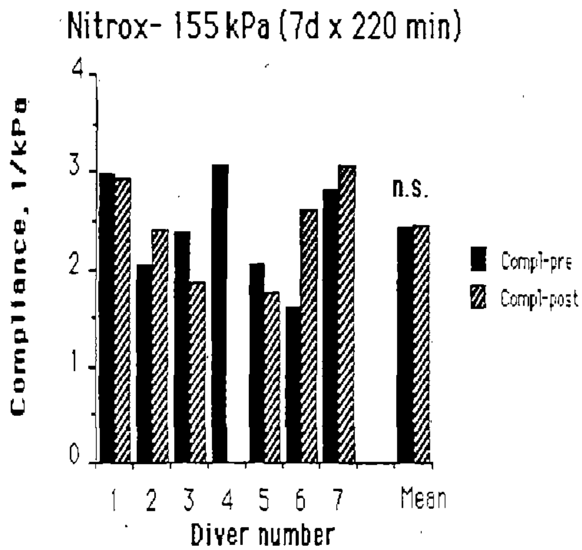
Difference Max Exp Flow 50% - predicted, pre - post nitrox 155 kPa O_2 (7d x 220min)



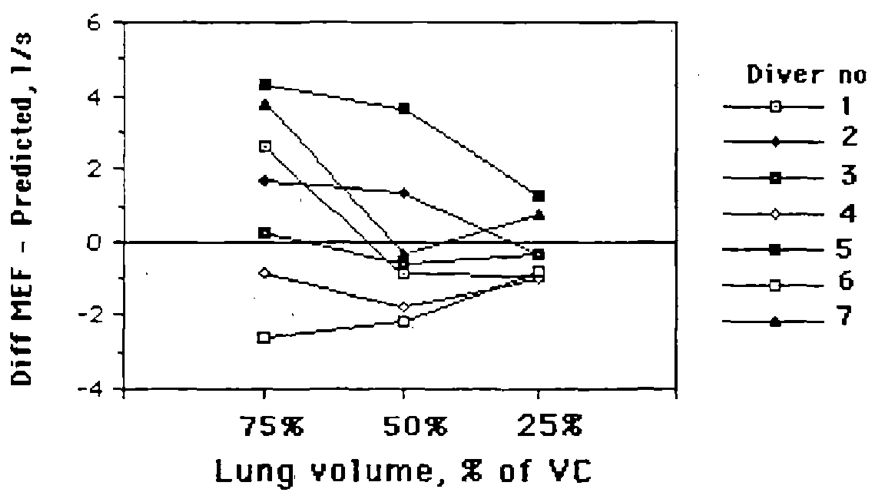
Difference Max Exp Flow 25% - predicted, pre - post nitrox 155 kPa O_2 (7d x 220 min)



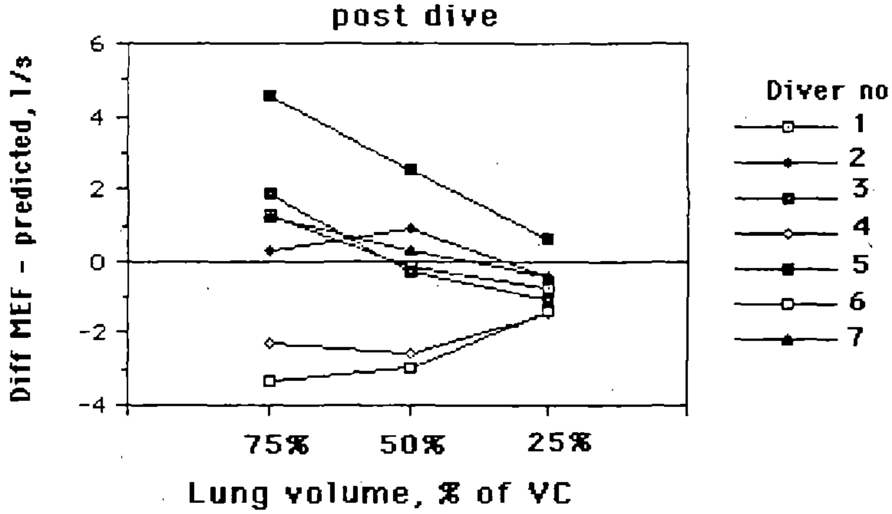




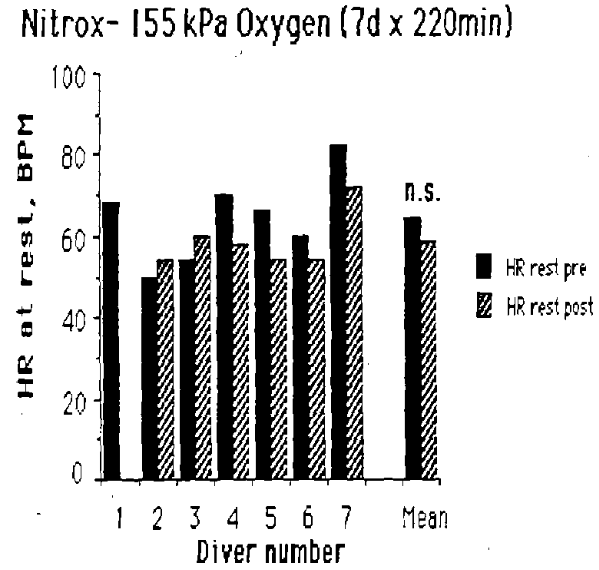
Maximum expiratory flows at different lung volumes
Predive

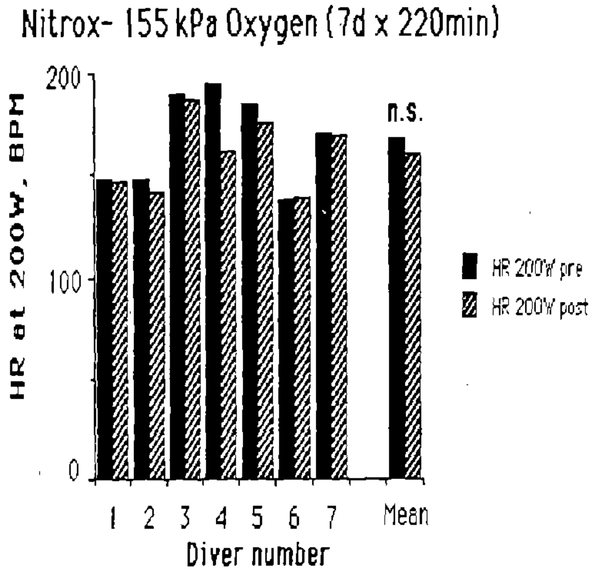


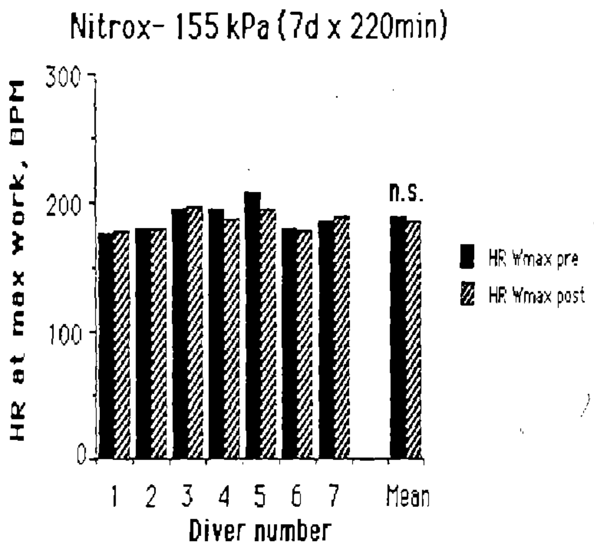
Maximum expiratory flows at different lung volumes
post dive

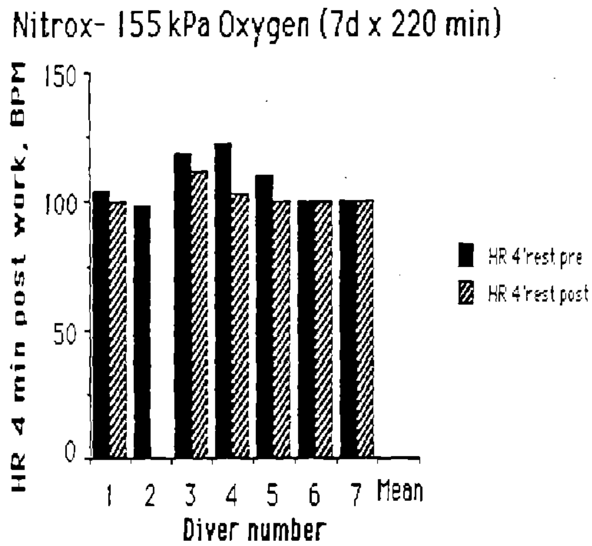


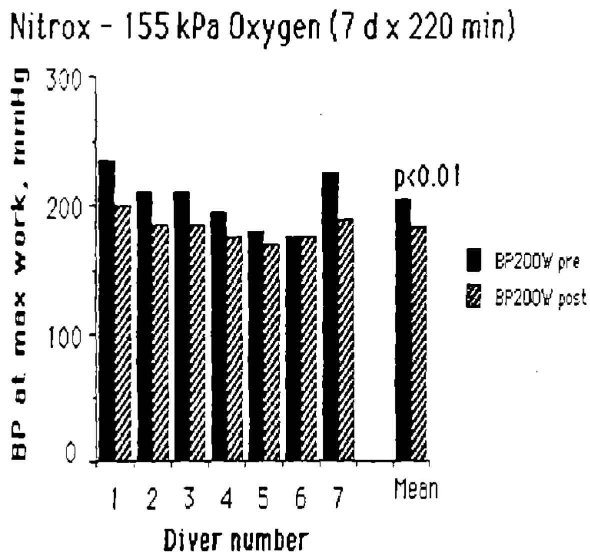
Ergometry data

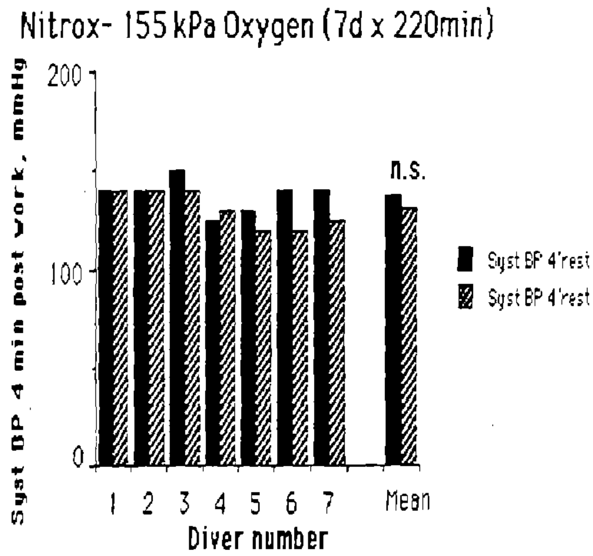


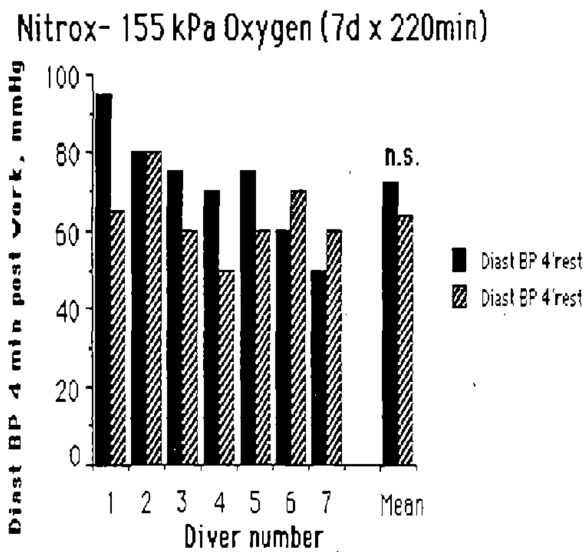


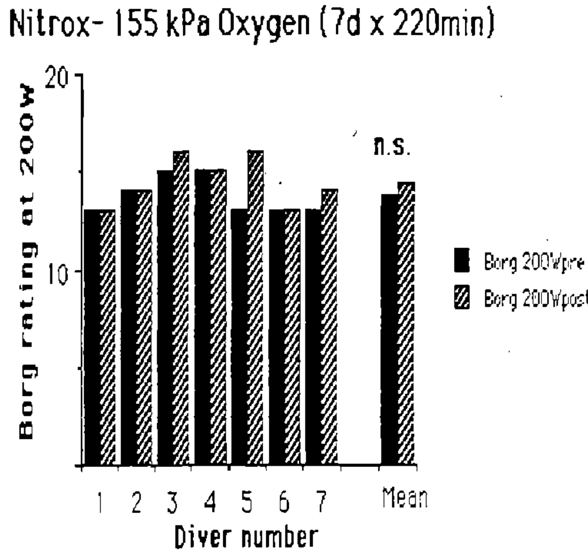


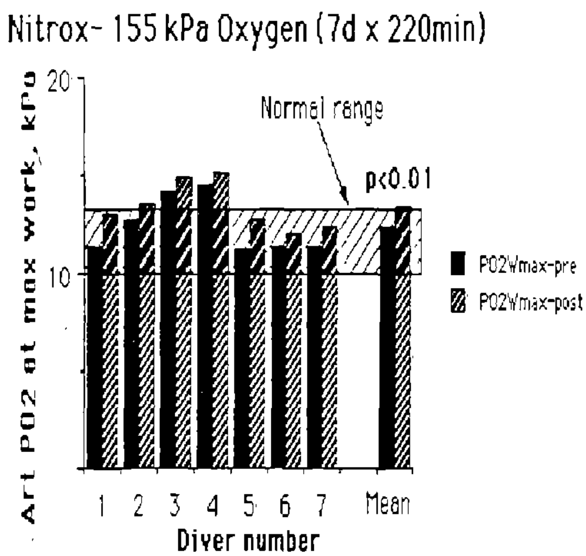


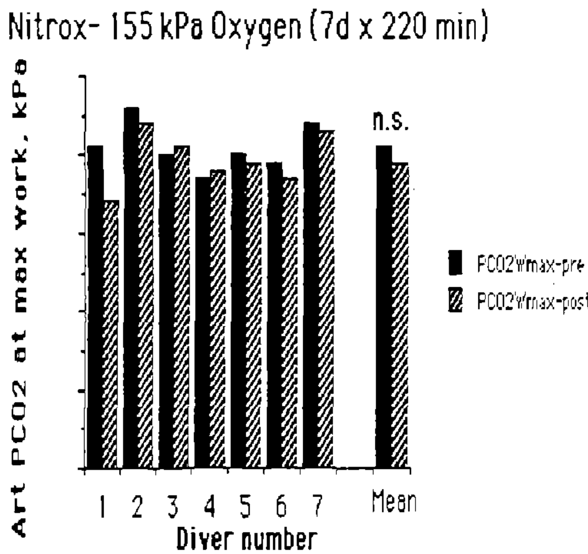


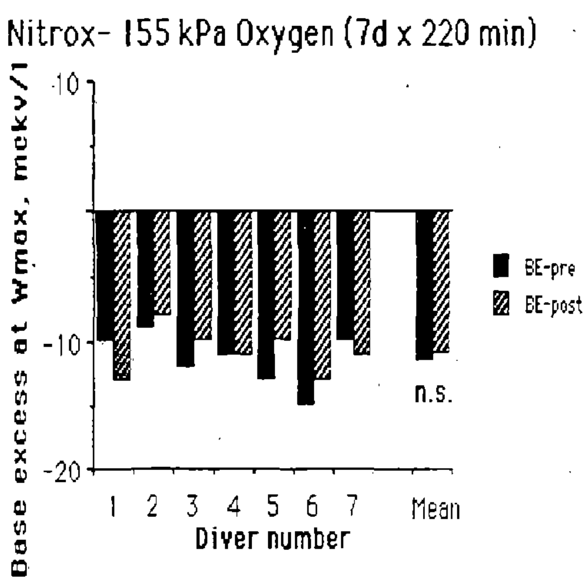


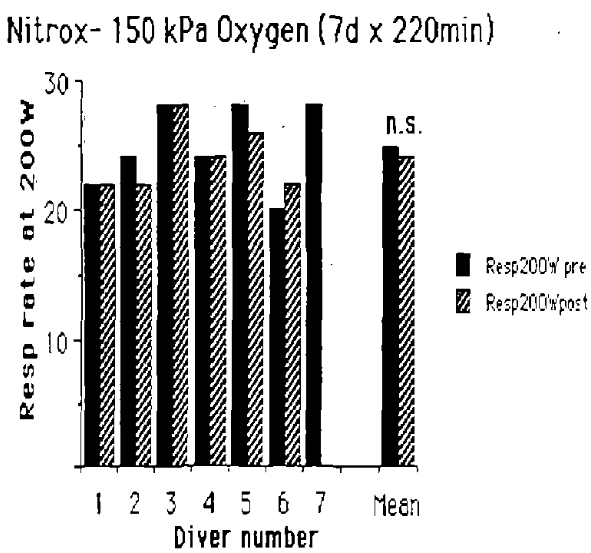

Nitrox- 155 kPa Oxygen (7d x 220min)
Diast BP 4 min post work, mmHg
100
80
60
40
20
0
n.s.
1 2 3 4 5 6 7 Mean
Diver number
Diast BP 4'rest
Diast BP 4'rest

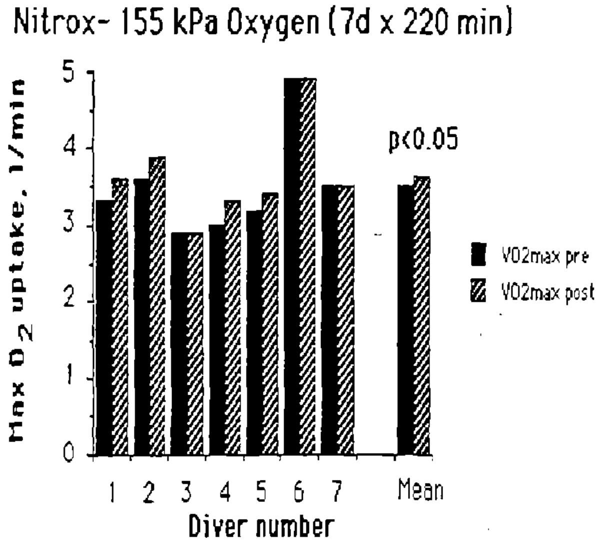

Nitrox- 155 kPa Oxygen (7d x 220min)
Borg rating at 200W
20
10
n.s.
1 2 3 4 5 6 7 Mean
Diver number
Borg 200W pre
Borg 200W post

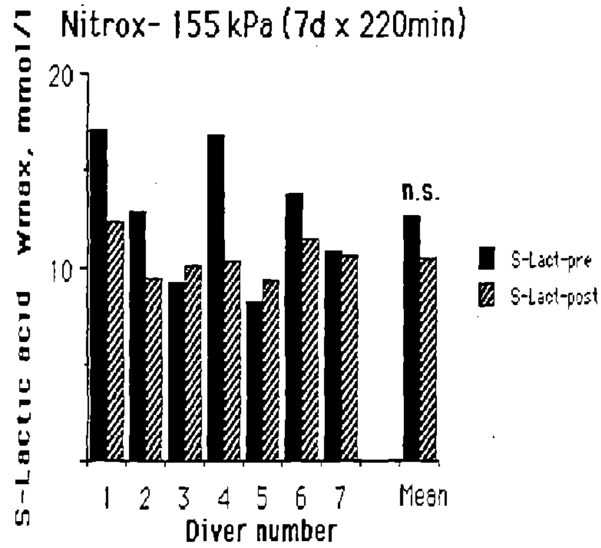

Nitrox- 155 kPa Oxygen (7d x 220min)
Art PO2 at max work, kPa
20
10
Normal range
p<0.01
1 2 3 4 5 6 7 Mean
Diver number
PO2Wmax-pre
PO2Wmax-post


Nitrox- 155 kPa Oxygen (7d x 220 min)
Art PCO2 at max work, kPa
n.s.
1 2 3 4 5 6 7 Mean
Diver number
PCO2Wmax-pre
PCO2Wmax-post

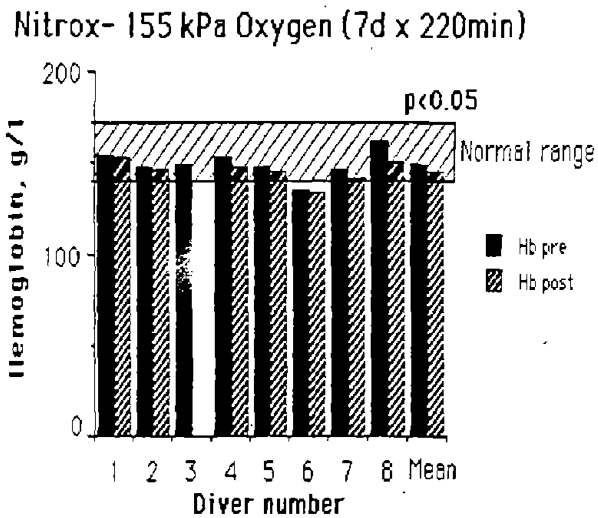

Nitrox- 155 kPa Oxygen (7d x 220 min)
Base excess at Wmax, mekv/l
10
-10
-20
n.s.
1 2 3 4 5 6 7 Mean
Diver number
BE-pre
BE-post

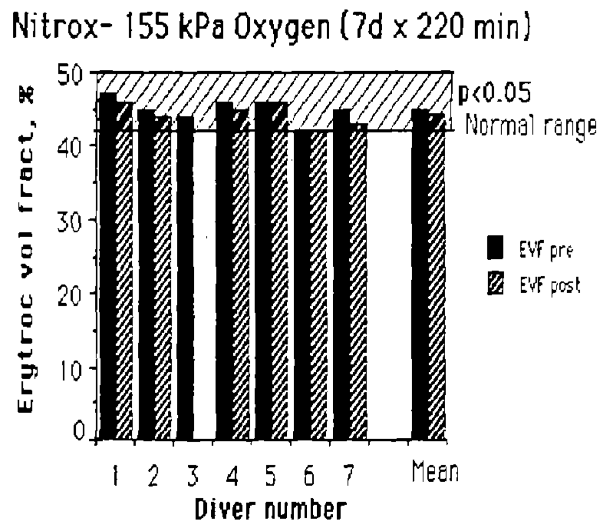

Nitrox- 150 kPa Oxygen (7d x 220min)
Resp rate at 200W
30
20
10
n.s.
1 2 3 4 5 6 7 Mean
Diver number
Resp200W pre
Resp200W post

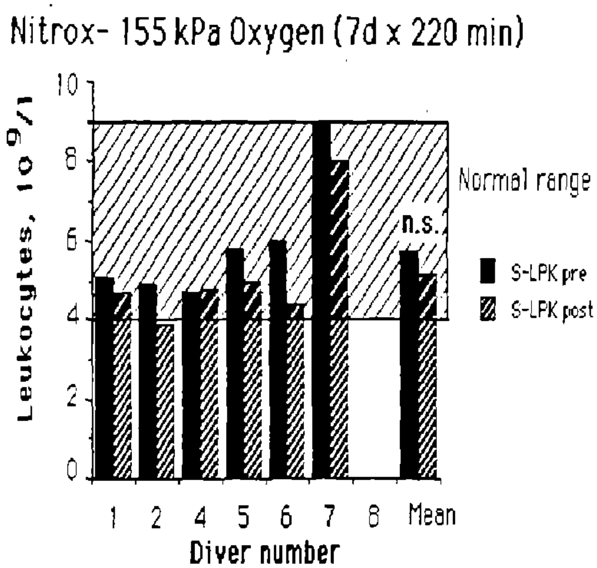


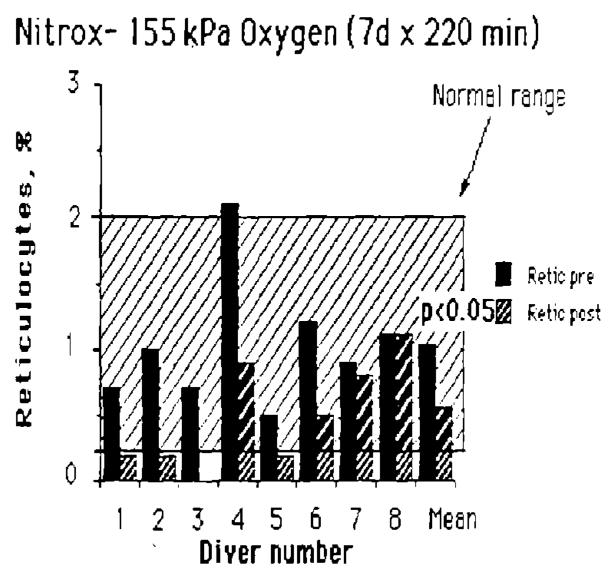


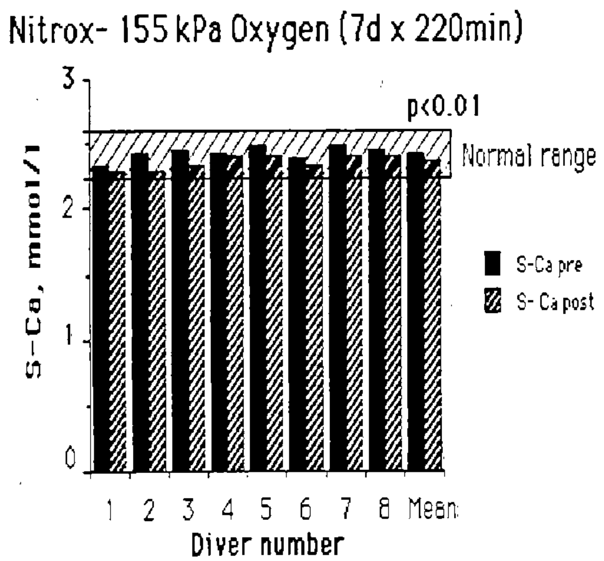
Blood parameters

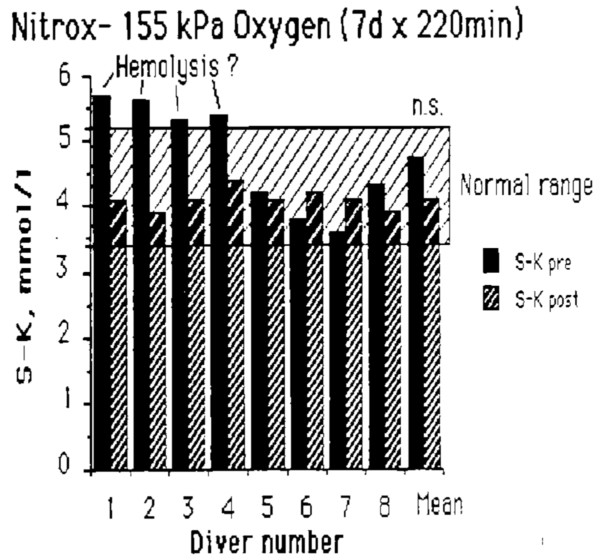


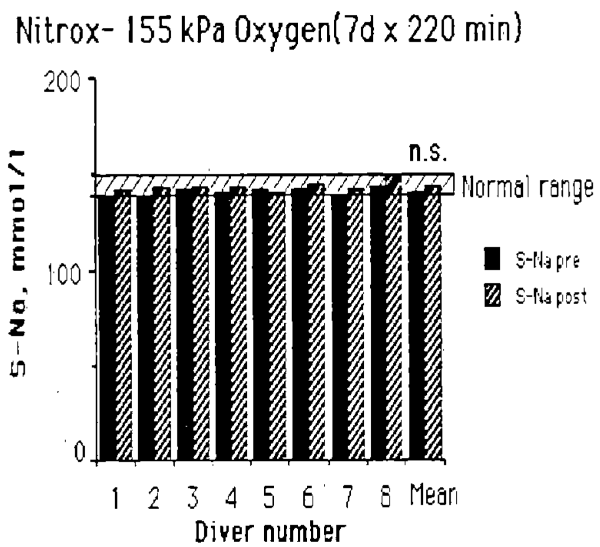


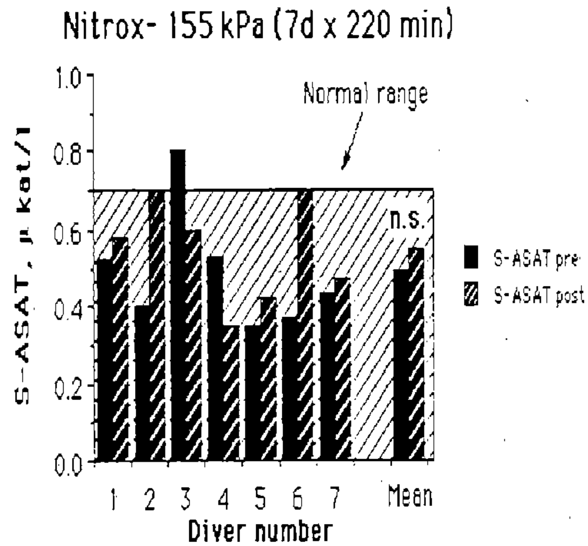


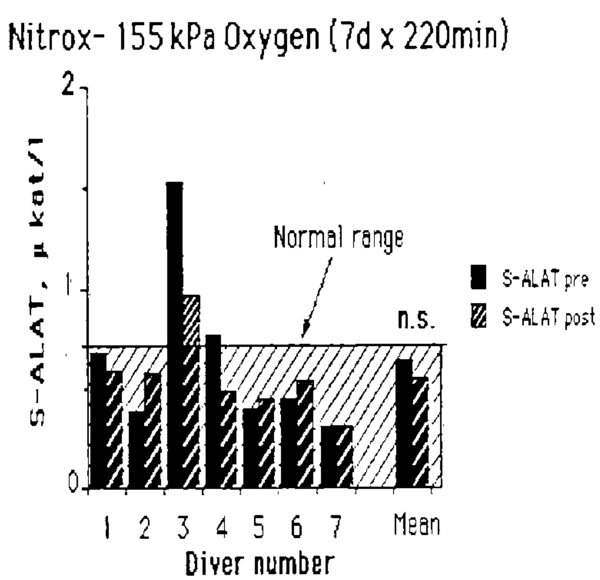



Nitrox- 155 kPa Oxygen (7d x 220min)
p<0.01
Normal range
S-Ca, mmol/l
S-Ca pre
S- Ca post
Diver number
1 2 3 4 5 6 7 8 Mean


Nitrox- 155 kPa Oxygen (7d x 220min)
Hemolysis ?
n.s.
Normal range
S-K, mmol/l
S-K pre
S-K post
Diver number
1 2 3 4 5 6 7 8 Mean


Nitrox- 155 kPa Oxygen(7d x 220 min)
n.s.
Normal range
S-Na, mmol/l
S-Na pre
S-Na post
Diver number
1 2 3 4 5 6 7 8 Mean


Nitrox- 155 kPa (7d x 220 min)
Normal range
n.s.
S-ASAT, µ kat/l
S-ASAT pre
S-ASAT post
Diver number
1 2 3 4 5 6 7 Mean


Nitrox- 155 kPa Oxygen (7d x 220min)
Normal range
n.s.
S-ALAT, µ kat/l
S-ALAT pre
S-ALAT post
Diver number
1 2 3 4 5 6 7 Mean

APPENDIX B

Profundior
atque
securior

MARINENS DYKERICENTRUM

1989-11-22

Nr 724

Sida 1 (3)

Sändlista

<u>Punktdykning med nitrox. Slutrapport om forskningsprojekt</u>

Härmed överlämnas slutrapport från rubricerade forskningsprojekt.

Rapporten består av följande delar

Del 1 Punktdykning med nitrox. Teknisk rapport

Del 2 Oxygen enriched air - "nitrox" - in surface oriented diving. Fysiologisk rapport m m

Del 3 Förslag till särskilda säkerhetsföreskrifter vid nitroxdykning

Del 4 Ekonomisk redovisning

Projektet har utförts vid Marinens Dykericentrum (MDC) i samarbete med Försvarets Forskningsanstalt, avd Navalmedicin (FOA58) under ledning av en projektgrupp bestående av

Björn Mohlin, projektledare, chef MDC
Bo Persson, teknisk ledare, MDC teknik
Hans Örnhagen, forskningsledare, chef FOA58

Projektet har haft till syfte att öka kunskaperna om de fysiologiska effekterna av och de optimala betingelserna för punktdykning med nitrox samt att på grundval härav möjliggöra metodens allmänna användning vid dykeriarbeten på djup mellan 10 och 30 m och detta på ett sätt, som leder till ökad effektivitet utan medförande av risker för fysiologiska skador hos dykaren.

Preceding page blank

P stadr ss:~ x 1' 130 '1 HÄRSFJÄRDEN Telefon: 0750-632 52

Projektresultaten innebär sammanfattningsvis, att tidigare i litteraturen dokumenterade positiva erfarenheter bekräftas och att det föreliggande forskningsprojektet icke givit några rön, som talar emot en fortsatt och allmän användning av nitroxmetoden vid arbetsdykning.

I avvaktan på att Arbetarskyddsstyrelsen (ASS) eventuellt utfärdar anvisningar för nitroxdykning rekommenderar projektgruppen att rapporten, Del 3 med "Förslag till särskilda säkerhetsföreskrifter vid nitroxdykning" tillämpas.

Projektet har möjliggjorts tack vare finansiellt stöd från STU, Arbetsmiljöfonden och Svenska Byggbranschens Utvecklingsfond samt ett antal intresserade myndigheter och industriföretag (se Del 4). Till samtliga dessa organisationer riktar projektgruppen ett stort tack.

Björn Mohlin

Björn Mohlin
Projektledare

Sändlista Nitroxrapport, första upplagan

STU (5 ex)
Arbetsmiljöfonden (4 ex)
SBUF
ADAB Diving AB
DYKAB Vattenbyggarna
Dykoma
DYKMA AB
Dyk & Sjötjänst
DIB
SYR
Bygghälsan
Dräger Svenska AB
Sjöfartsverket
Stena AB
Interspiro AB
Södra Skogsägarna
Kustbevakningen
Vattenfall

Kopia av rapporten i denna version till:

Gunnar Lundborg, ASS
Bo Tengblad, Byggförbundet
Hans Örnhagen, FOA 58
Anders Muren, FOA 58

Som orientering

CM
C 1.ubflj
FMV
FOA 58
ASS

(Försöksdykarna får rapport, andra upplagan)

INTERSPIRO

Interspiro's Nitrox-blandare

Ref. Dataspecifikation 70.03.31

Princip

Nitrox-blandningen erhålles genom att luft och oxygen av *lika tryck* får strömma ut genom varsin ventilöppning, till en gemensam ledning. Där blandas gaserna och förs sedan genom en dykslang vidare till dykaren.

Genom att tryckfallet över ventilöppningarna är lika, kommer luftflödet att förhålla sig till oxygenflödet nästan som luftventilens och oxygenventilens öppningsareor förhåller sig till varandra.

Summan av ventilareorna bestämmer blandningsflödets storlek.

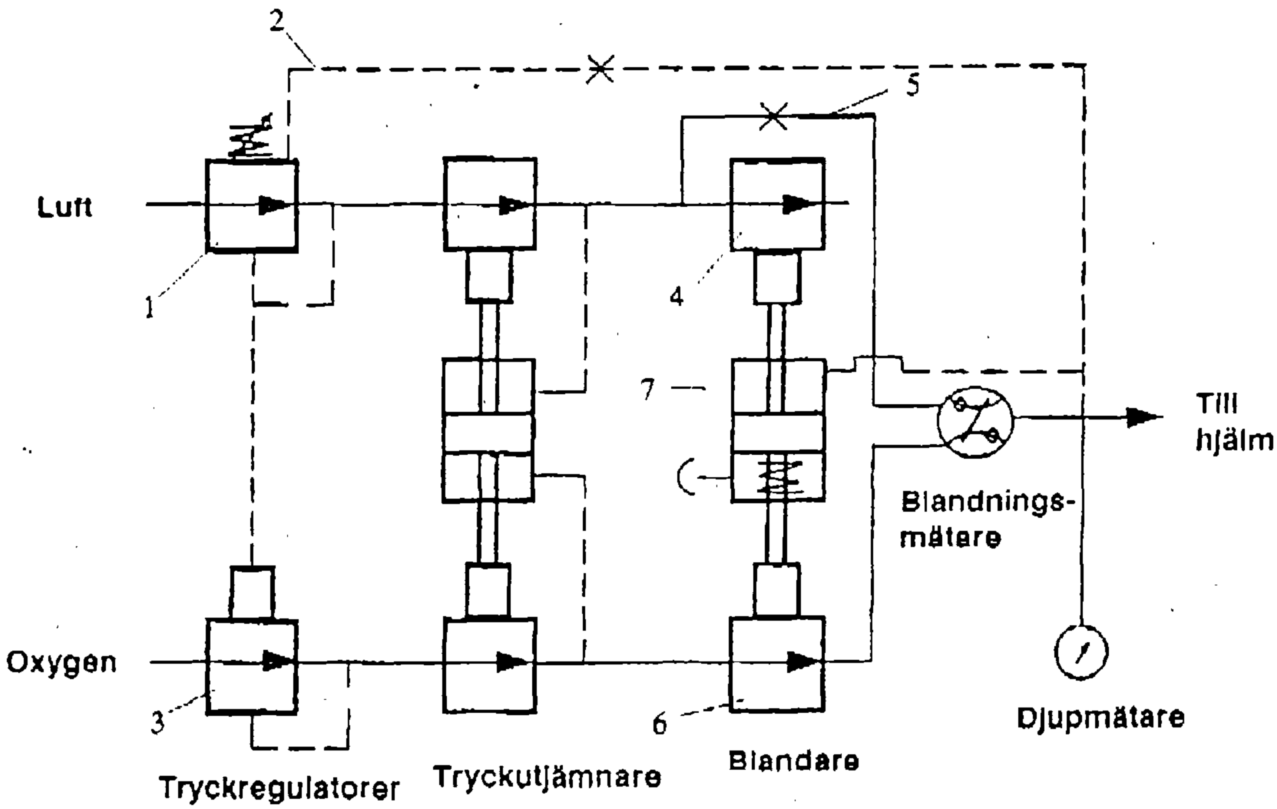
Ventilernas öppningsförhållande styrs av en gemensam ventilkropp. När oxygenhalten skall ökas förskjuts ventilkroppens läge. Den ökar då oxygenventilens area, samtidigt som den minskar luftventilens area. När oxygenhalten skall minskas gäller det omvända.

För varje läge hos ventilkroppen erhålles således ett bestämt blandningsförhållande mellan luft och oxygen.

Ventilkroppens läge styrs av en fjäderbelastad kolv, som via mottrycket i dykslangen känner av dykdjupet.

Genom att ge ventilerna en öppningsgrad avpassad som funktion av dykdjupet, kan man optimera nitroxblandningen enligt fig. 1 i Dataspecifikation 70.03.31.

Blandningsapparat för slangdykning - Symbolschema



Beskrivning enligt symbolschema.

1. Luftregulator med ställbart övertryck relativt tryckdjup.

2. Ledning för återkoppling av tryckdjup till luftregulatorn.

3. Oxygenregulator som styrs av övertrycket från luftregulatorn. Vid luftavbrott stängs oxygentillförsel automatiskt av. När luftövertrycket ändras så ändras oxygentrycket lika mycket. Luftregulatorinställningen kan således användas för att justera nitroxflödets storlek.

4. Luftventil.

5. Luftshunt.

6. Oxygenventil.

7. Styrkolv. Fjädern är stallbar varigenom blandningskurvans "läge" kan justeras.

2 Gasmischgerät POLYCOM

Aufbau und Funktion

2.1 Allgemeines

Neben der eigentlichen Mischereinheit (1), die wahlweise die genannten Atemgasgemische mit einer Genauigkeit von ± 1 Vol.-% O_2 erzeugt, ist im Polycom zur Überwachung aller Gasversorgungsdrücke und der O_2-Konzentration ein umfangreiches Sicherheitssystem vorhanden, das sich aus den im Schaubild herausgestellter Komponenten zusammensetzt

- o Pneumatisches Warnsystem (2)
- o Elektrisches Warnsystem (3)
- o Notversorgungssystem (4)
- o Anzeige der Gasversorgungsdrücke (5)
- o Schutzeinrichtung (6).

Bei einer max. Mischgaslieferleistung von 1200 L/min mit konstantem Ausgangsdruck von 20 bar ist das Gerät für die gleichzeitige Versorgung von 2 Tauchern geeignet.

Der kompakte übersichtliche Aufbau des Gerätes ermöglicht eine einfache und sichere Bedienung.

2.2.1 Gasmischer

In dem Gerät werden die Komponentengase nach dem "Konstant-Flow-Prinzip" zusammengeführt, d. h. auch bei wechselnden Mischgasentnahmemengen wird das Druckgefälle an der Dosiereinrichtung 15-18 konstantgeregelt. Auf der Zustromseite sind domgesteuerte Druckregler 10, 11 angeordnet, die in Abhängigkeit vom Druck im Mischgasspeicher 20 über eine elektro-pneumatische Steuerung 12, 23

...

intermittierend zu- oder abgeschaltet werden. Für den gleichbleibenden Druck auf der Abstromseite der Dosiereinrichtung 15-18 ist der Rückdruckregler 19 vorgesehen.

Durch einfaches Umschalten der Ventile 13, 14 wird das jeweils gewünschte Gasgemisch eingestellt.

Der vom Druckminderer 22 geregelte Mischgasdruck am Geräteausgang beträgt 20 bar.

2.2.2 Pneumatisches Warnsystem

Das pneumatische Warnsystem dient zur Überwachung

der Gasdrücke
- Sauerstoff
- Druckluft
- Notversorgung
- Mischgas

der Mischerfunktion
und der Stromversorgung.

Beim Auftreten einer Störung wird akustisch mit der Hupe 29 und optisch mit dem Schauzeichen 26 gewarnt. Das für die Schaltung vorgesehene Magnetventil 25 ist mit dem Druckschalter 4 (Notversorgung) und dem Druckschalter 5 (Mischgas) elektrisch in Reihe geschaltet. Bei Unterbrechung des Stromkreises - ausgelöst durch Gasmangel oder Stromausfall - wird das Warnsystem eingeschaltet.

Die Druckschalter - Druckluft 3, Sauerstoff 2 und Mischgas 23 sind mit dem für die Mischbesteuerung eingesetzten Magnetventil 12 so in Reihe geschaltet, daß bei Gasmangel am Eingang (O_2 oder Druckluft) der Mischer selbsttätig außer Betrieb gesetzt wird.

...

Infolge des dann sinkenden Gasdrucks im Speicher 20 wird das akustische und optische Warnsignal vom Druckschalter 5 ausgelöst.

2.2.3 Elektrisches Warnsystem

Mit dem elektrischen Warnsystem, also dem O_2-Meßgerät Oxytron 27, wird die O_2-Konzentration im Mischgas (vom Mischer und der Notversorgung) überwacht.

Wird die vorgewählte O_2-Konzentration im Mischgas um mehr als $\pm$ 2 Vol.-% O_2 überschritten, so ertönt ein Warnsignal (Hupe 28). Die Störung wird gleichzeitig durch Blinkzeichen am Oxytron 27 angezeigt. Das akustische Signal kann mit Hilfe eines Drucktasters gelöscht werden.

2.2.4 Notversorgungssystem

Die im Gerät integrierte Schalteinrichtung ermöglicht beim Auftreten einer Störung in der Gasversorgung oder am Gasmischer durch Betätigen eines Ventiles 24 die schnelle Umschaltung vom Mischerbetrieb auf die Notgasversorgung.

Als Notgas wird vorzugsweise Mischgas gemäß der am Mischer vorgewählten O_2-Konzentration in zusätzlichen Gasflaschen gespeichert. Die Vorratsmenge sollte so groß sein, daß in Notfällen ein sicheres Austauchen des Tauchers möglich ist.

...

2.2.5 Anzeige der Gasversorgungsdrücke

Alle Gasversorgungsdrücke - Sauerstoff, Druckluft, Notversorgung, Mischgas - werden mit eingebauten Druckmessern 6-9 angezeigt.

2.2.6 Schutzeinrichtung

Gegen ungünstige Einflüsse - Witterung, Seewasser usw. - wird das Gerät durch ein Gehäuse sicher geschützt. Der Innenraum wird ständig mit einer Luftmenge von 5 L/min (Ventil 1) gespült. Dadurch wird verhindert, daß bei einer evtl. auftretenden Leckage sich im Gehäuse eine erhöhte Sauerstoffkonzentration ausbildet, die in Gegenwart von elektrischen Geräteeinheiten, wie z. B. das Oxytron, eine Gefahr darstellen könnte.

2.3 Technische Daten

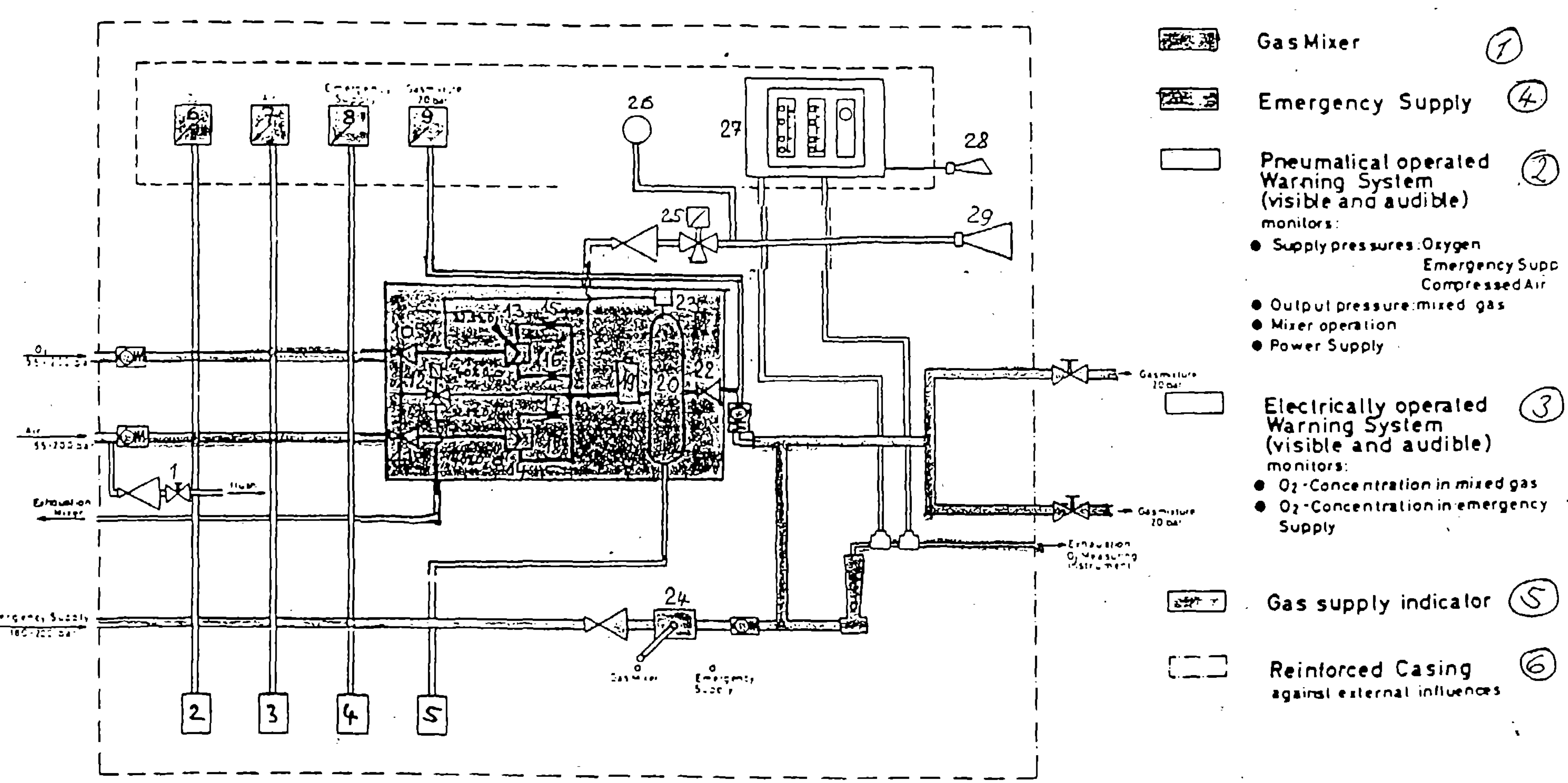
zu mischende Gase	: Sauerstoff/Druckluft
Eingangsdrücke der Gase	: mind. 55 bar - max. 200 bar
Hilfsenergie	: 220 V - 50 Hz
Mischgenauigkeit	: ± 1 Vol.% Sauerstoff
Reproduzierbarkeit	: ± 1 Vol.% Sauerstoff
Ausgangsdruck des Mischgases	: 20 bar
Mischgas-Lieferleistung	: Vmin 2 N L/min
	Vmax 1.200 L/min

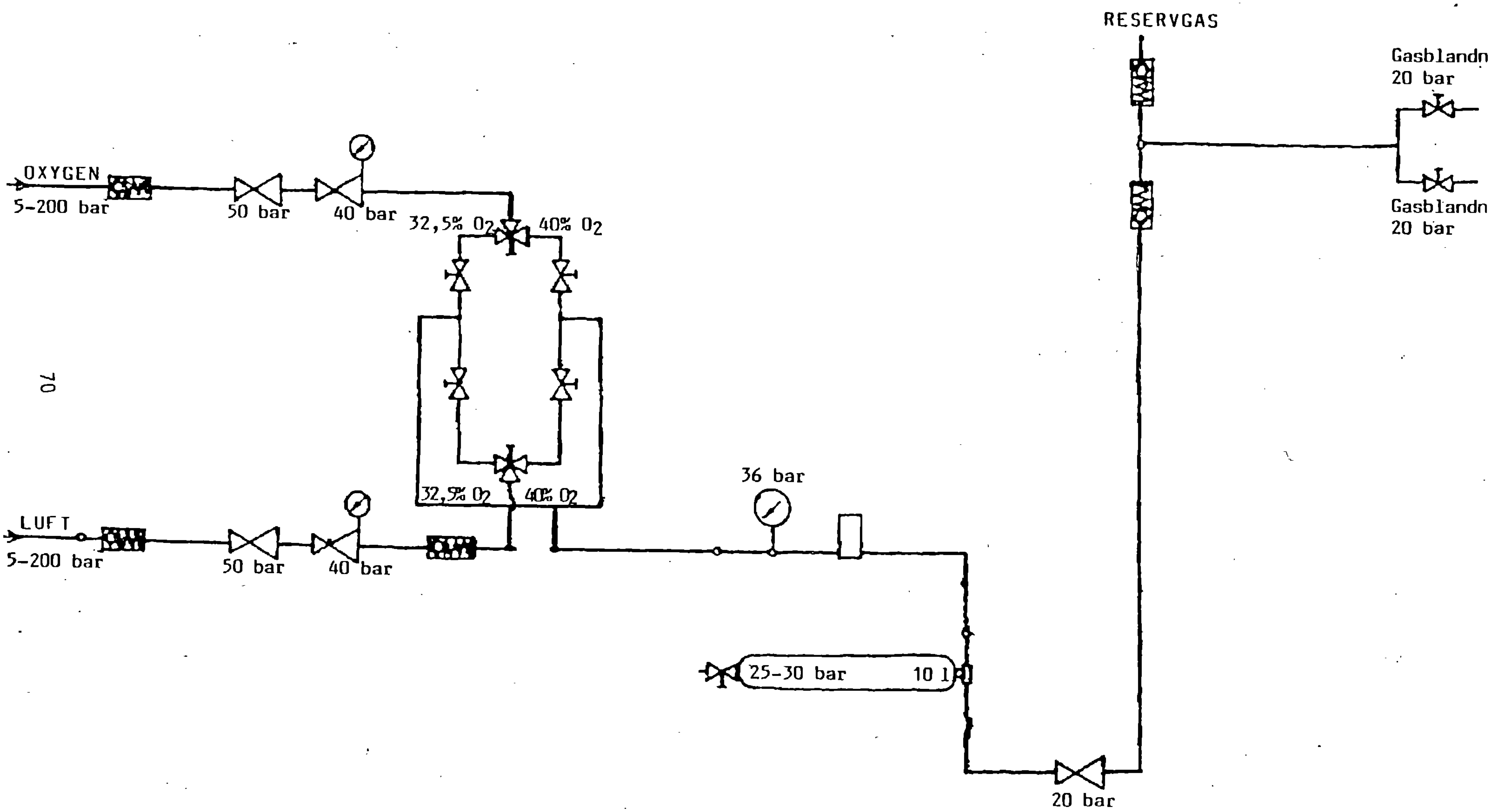
<u>Sicherheits-Einrichtungen:</u>
- Überwachung der Eingangs- und Mischgas-Drücke,
- Kontrolle der Sauerstoff-Konzentration,
- Bypass-Schaltung für die Not-Versorgung.

Gewicht	: ca. 192 kg
Abmessungen	: ca. 1.500 mm lang
	ca. 930 mm hoch
	ca. 315 mm tief

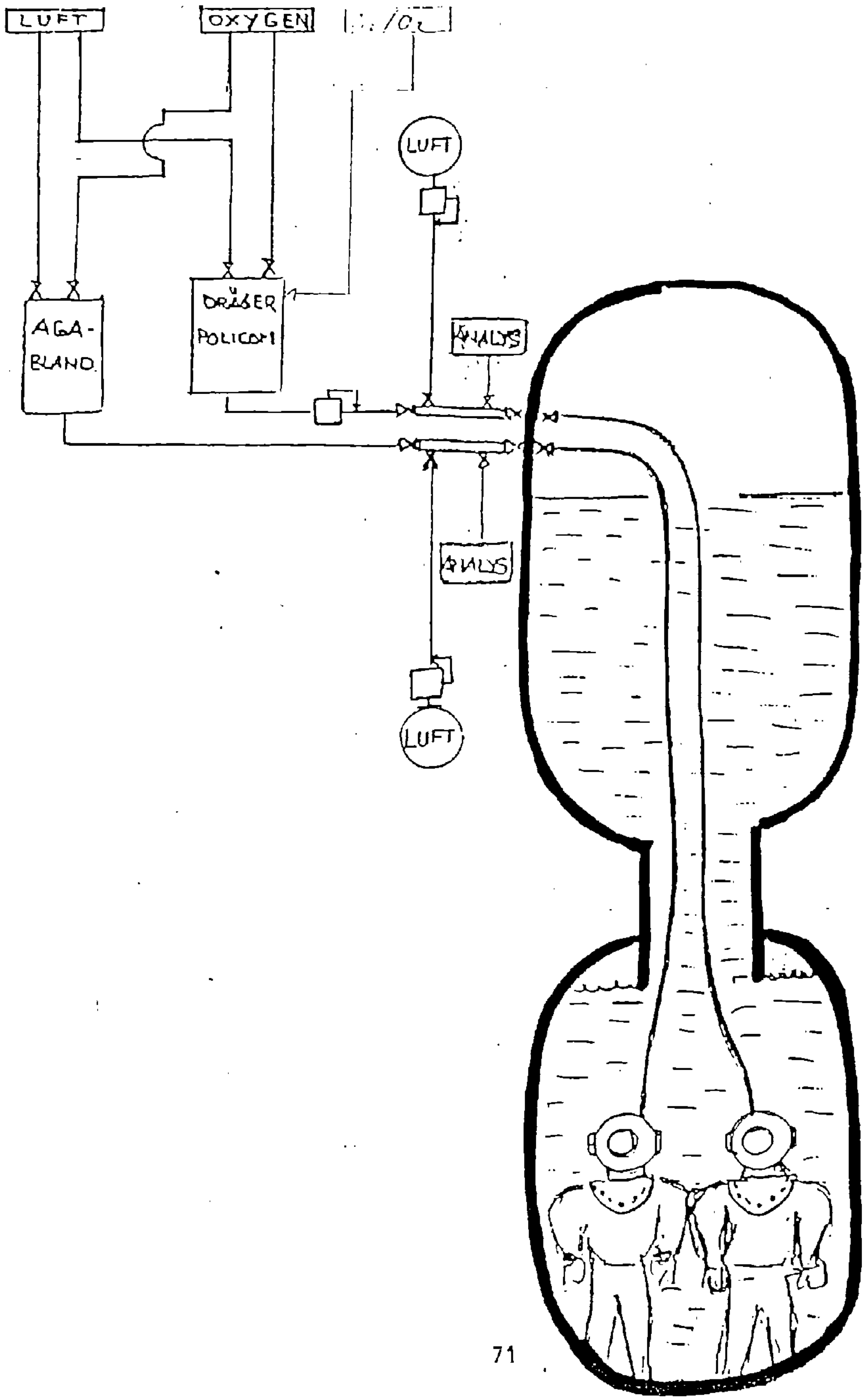
...

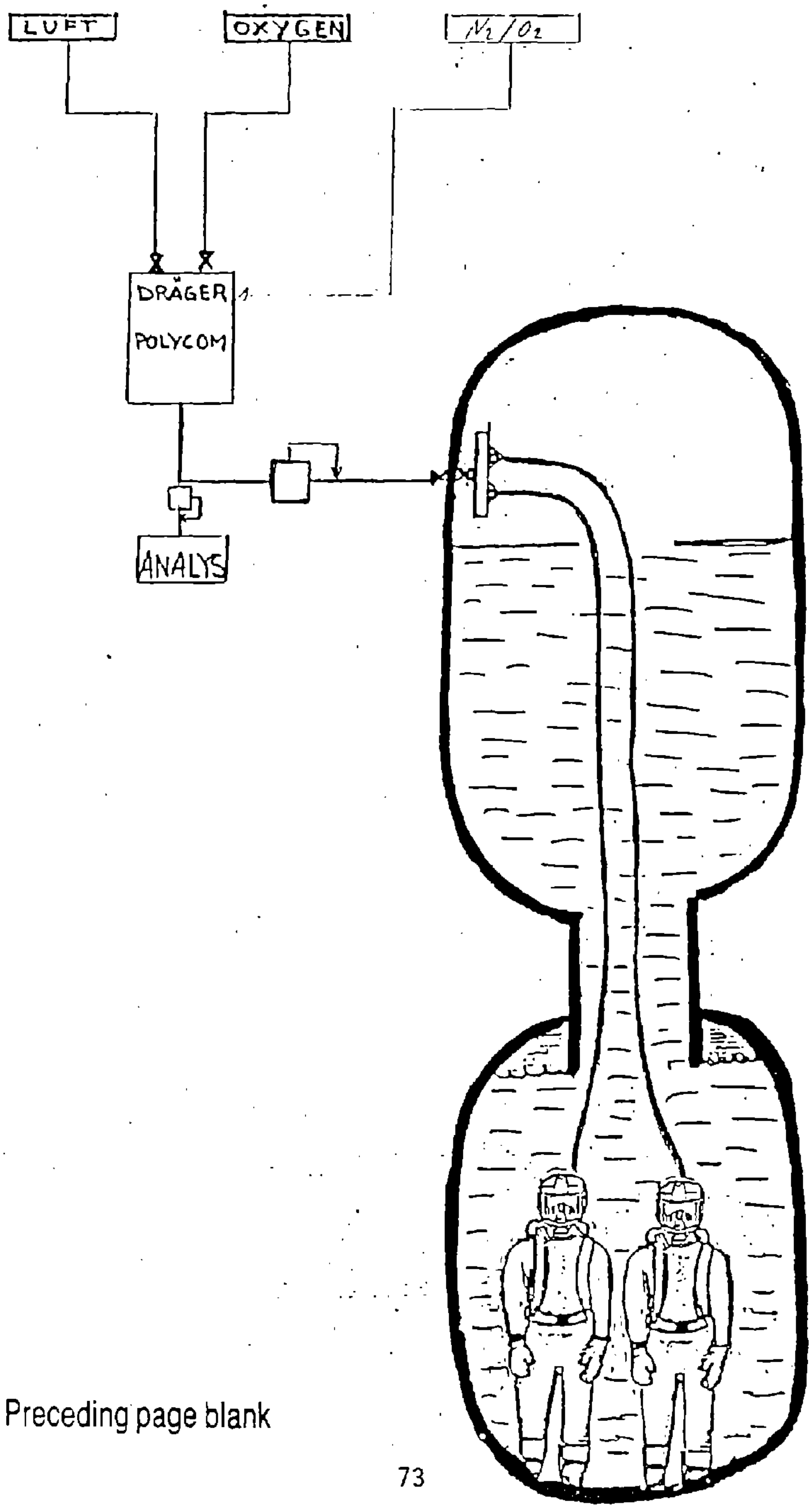
Polycom101 Gas Mixer





Polycom 101 D21300 Schematic view of mixer


LUFT
OXYGEN
LUFT
DRÄGER
POLICOM
AGA-
BLAND
ANALYS
ANALYS
LUFT



Preceding page blank

Del 1

Punktdykning med nitrox. Teknisk rapport

1. Allmänt

Projektets ändamål har varit att undersöka om användning av en andningsgas bestående av N_2 och O_2 (nitrox) med högre O_2-halt än i luft kan göra punktdykningar säkrare och effektivare.

I projektet ingående dykningar har genomförts i MDC kammarsystem (AK och US) i två perioder. Vid dykningar i period 1 användes tung utrustning och i period 2 lätt utrustning.

I varje period deltog fyra dykare. Varje dykare gjorde en dykning per dag under sju på varandra följande dagar. Dykdjupet var 21 m med 220 min expositionstid och därefter direktuppstigning. Andningsgasen bestod av 50% N_2 och 50% O_2.

2. Gasförsörjning

2.1 Gaser

2.1.1 Andningsgas

Dykarna försågs med andningsgas 50% N_2 och 50% O_2 via gasblandare, som blandade luft och oxygen. Under dykningarna period 1 (tung dykutrustning) försågs en av dykarna med gas via Interspiro nitroxblandare och den andre via Dräger ./1
Polycom 101. ./2

Vid dykningarna period 2 (lätt dykutrustning) försågs båda dykarna med gas via Dräger Polycom 101.

2.1.2 Reservgas

Färdigblandad gas, 50% N_2 och 50% O_2, fanns i förråd för omedelbar inkoppling till dykarna ifall haveri skulle inträffa på blandarna eller om av någon anledning osäkerhet beträffande andningsgasens sammansättning skulle uppstå.

2.1.3 Nödgas

I beredskap, för omedelbar inkoppling, fanns luft om någon av dykarna skulle få symptom på akut O_2-förgiftning.

2.2 Gasdistribution

2.2.1 Gasdistribution period 1

Blandarna matades med luft och O_2 från MDC ordinarie gas-förråd. Till Dräger Polycom 101 var även reservgasförrådet anslutet. Från Interspiro nitroxblandare gick gasblandningen direkt till en samlingslåda och därefter genom kammarvägen ner till dykaren. I samlingslådan fanns uttag till O_2-analysator. Till samlingslådan var även luftförrådet anslutet via en reduceringsventil. Från Dräger Polycom 101 gick gasblandningen via en flödesregulator typ Dräger Taucherautomat till en samlingslåda. Inkopplingen i övrigt enligt beskrivning ovan. ./3

2.2.2 Gasdistribution period 2

Dräger Polycom 101 matades med luft och O_2 från MDC ordinarie gasförråd samt med reservgas. Från blandaren gick gasen till en pilotstyrd reducering och därifrån in till en uttagslåda i AK. På ledningen mellan blandare och reducering fanns uttag till O_2-analysator. Från uttagslådan i AK leddes gasen via slang till dykapparaternas ytluftförsörjningsnippel. ./4

3. Övervakning

3.1 Dyksäkerhetsmässig övervakning

Under hela dykningen hade dykarledaren talkommunikation med dykarna. Dykarna övervakades dessutom via TV-monitor. Talkommunikation och TV-bild bandades och sparades minst 24 h efter respektive dykning. Ingående gas till dykarna analyserades kontinuerligt med avseende på O_2-halt.

3.2 Medicinsk övervakning

3.2.1 Läkarundersökning

Dykarna undersöktes omedelbart före och efter varje dykning, enligt speciellt protokoll, av dykarläkare.

3.2.2 Hjärtfrekvens

I första försöksomgången (tung utrustning) övervakades växelvis de båda dykarnas hjärtfrekvens med EKG. I andra försöksomgången slopades EKG-övervakningen av praktiska skäl efter första dagens dykningar. Signalförstärkaren (80 x 40 mm), som placerats innanför dräkten, visade sig utgöra ett hinder med den viktbälteskombination som användes.

3.2.3 Övervakning av gas i andningszonen

Under dykningarna togs gasprov från hjälmarna respektive helmaskerna via en kapillärslang till en masspektrometer Centronic 200 MGA. Vid tungdykning var kapillärens mynning monterad i hjälmen mellan frontglasets underkant och anslutningen för bröstplåten. Vid lättdykning var kapillärens mynning instucken i inhalationsmasken. Kapillären från respektive dykare anslöts växelvis till masspektrometern. På instrumentet kunde gassammansättningens variationer (O_2, CO_2 och N_2) följas andetag för andetag. En skrivare var kopplad till masspektrometern, på vilken registrering gjordes var 30.minut.

4. Dykutrustning

4.1 Tung utrustning

Vid dykningar period 1 användes marinens standardutrustning för tungdykning med den så kallade Karlskronahjälmen. Hjälmen är försedd med luftavledningskanal (LUAK).

4.2 Lätt utrustning

Vid dykning period 2 användes dykapparat Scubapro Navy med AGA helmask MK II. Dräkten var av konstantvolymtyp.

5. Brandskydd

Ledningar, slangar, armatur och dykmateriel, som kom i kontakt med nitroxgas, rengjordes som om de skulle använts för ren O_2.

Efter respektive dykning fick dykarna ta av sig dräkt och underställ på ett ställe, väl avskilt från elektrisk utrustning, som kunde förorsaka gnistbildning. Rökförbud gäller generellt i MDC kammarhall och i övriga utrymmen, där gas hanteras.

Dykarna uppmärksammades på att hår och skägg kunde vara bemängda med O_2-rik gas.

6. Dykprocedurer

6.1 Dykning med tung utrustning

Dykarna tog på sig dykutrustning, utom hjälm, utanför kammaren. Härefter gick dykare 1 in i AK, där han försågs med hjälm, ansluten till Interspiro nitroxblandare. Efter verkställd funktionskontroll av gasförsörjning, EKG-övervakning och kommunikation sattes frontglaset på och dykare 1 sändes ner i vattnet i AK. Efter verkställd täthetskontroll av dykare 1 äntrade dykare 2 AK och försågs med hjälm, ansluten till Dräger Polycom 101. Efter genomförda funktionskontroller sändes dykare 2 ner i vattnet i AK. Efter verkställd täthetskontroll sändes dykare 1 ner i US omedelbart följd av dykare 2. Expositionstid räknades från det att dykare 1 påbörjade nedstigning till US. När båda dykarna kommit på plats i US genomfördes trycksättning så att djupet i US motsvarade 21 m. Under tiden på djup var dykarna sysselsatta med arbeten av olika slag. Arbetsuppgifterna var så valda att dykarnas fysiska ansträngning skulle motsvara vad de presterar vid normala dykningar.

Efter 220 min expositionstid påbörjades uppstigning med 10 m/min direkt till ytan. När AK kommit till ytan (US på 4 m) skiftades gasförsörjning till dykare 2 över till luft för att minska O_2-halten i dräkt och underställ och därigenom minska brandrisken (för dykare 1 skedde detta med automatik i och med att Interspiro nitroxblandare anpassar O_2-halten till djupet). Dykare 1 togs upp i AK och därefter dykare 2. Härefter togs dykare 1 upp ur vattnet och hjälmen togs av och övriga anslutningar lossades. Förfarandet upprepades med dykare 2.

6.2 Dykning med lätt utrustning

Dykarna tog på sig underställ och dykardräkt utanför kammaren. Dykare 1 tog plats i AK och försågs med vikter och dykapparat. Dykare 1 tog på mask, varefter kontroll av gasförsörjning och kommunikation genomfördes innan dykare 1 gick ner i vattnet i AK för funktionskontroll. Dykare 2 äntrade AK och genomförde samma procedur som dykare 1. Härefter sändes dykare 1 ner i US, omedelbart följd av dykare 2. När båda dykarna var på plats i US genomfördes trycksättning till 21 m. Under tiden på djup var dykarna sysselsatta med arbeten av olika slag.

Efter 220 min påbörjades uppstigning med 10 m/min direkt till ytan. När AK kommit till ytan (US på 4 m) togs dykare 1 upp i AK och därefter dykare 2. Härefter togs dykare 1 upp ur vattnet och dykapparaten togs av. Förfarandet upprepades med dykare 2.

Del 3

Förslag till särskilda säkerhetsföreskrifter vid nitroxdykning

Vid dykning med oxygenrik gasblandning skall följande iakttas:

- Armatur, rörledningar och övrig materiel, som kommer i kontakt med gasblandningen, skall uppfylla samma fordringar som vid användning av 100% oxygen.

- Rökning eller användning av apparat som kan förorsaka gnistbildning får ej förekomma inom område där risk för ansamling av oxygen eller oxygenrik gasblandning kan förekomma.

- Vid matning av gas till dykaren från blandare skall kontinuerlig analys av gasen utföras. Uttag av gas till analysator skall göras så nära dykaren som möjligt.

- Om fel på gasblandningen uppstår skall reservgas omedelbart kunna kopplas in.

- Vid användning av färdigblandad gas skall behållarens innehåll analyseras omedelbart innan behållarna ansluts till dyksystemet.

- Upptäcker dykaren tecken på O_2-förgiftning skall han omedelbart avbryta arbetet samt anmäla detta till dykareledaren. Är dykaren i vattnet skall luft inkopplas till dykaren.

- Vid svetsnings- och skärningsarbeten skall åtgärder vidtagas så att svetsloppor eller sprut ej kan penetrera dykarens dräkt.

- pO_2 får ej överskrida 140 kPa. Beräknas dykningen bli ansträngande eller risk för CO_2 förhöjning föreligger bör pO_2 reduceras.

- O_2-dosen bör ej överskrida värdena i tabell 1. OTU (oxygen tolerance unit) beräknas med hjälp av tabell 2.

Tabell 1

Maximalt tillåten O_2-dos

Operationens varaktighet (dagar)	Daglig O_2-dos (OTU)
1	850
2	700
3	620
4	525
5	460
6	420
7	380
8	350
9	330
10	310
11	300
12	300
13	300
14	300
15-30	300

Tabell 2

OTU per tidsenhet vid olika pO_2

pO_2 (kPa)	OTU (/min)	OTU (/h)
60	0.26	16
70	0.47	28
80	0.65	39
90	0.83	50
100	1.0	60
110	1.16	70
120	1.32	79
130	1.48	89
140	1.63	98

Del 4

Ekonomisk redovisning

Bidragsgivare	Kronor
STU (förprojekt)	100.000
STU (huvudprojekt)	335.000
MDC (kammaranl)	195.044
FOA	50.000
Arbetsmiljöfonden	50.000
SBUF	90.000
Stena AB	15.000
Kustbevakningen	25.000
Interspiro	25.000
Vattenfall	25.000
Södra skogsägarna	25.000
Sjöfartsverket	20.000
DIB/SYR	200.000
Dräger	25.000
Summa	1.180.044

Kostnader	Kronor
FOA (arbetskostnad)	200.000
KS (undersökn)	75.000
MDC (kammarhyra)	252.600
MDC (mtrl)	17.365
MDC (gas, flaskkyra)	71.548
MDC (arbetskostn)	329.700
Resor, måltoder etc	11.484
Arvoden dykare	212.347
Tryckning	10.000
Summa	1.180.044