USE OF TWO PRIMARY BREATHING MIXTURES FOR ENRICHED AIR DIVING OPERATIONS

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In 1987, the National Undersea Research Center at the University of North Carolina at Wilmington (NURC/UNCW) began using "optimal" Enriched Air Nitrox (EAN) mixtures with Equivalent Air Depth (EAD) diving techniques as a means of increasing bottom time and operational flexibility. Experience during the past two years has shown significant advantage of the EAD technique over NOAA Nitrox I. However, the use of optimal EAD techniques complicates logistics since different mixtures are required to compensate for minor depth changes. Based on NURC/UNCW's experience conducting a combination of over 700 NOAA Nitrox I and EAD dives, two EAN mixtures, 32% and 36%, can effectively provide optimal bottom times while simplifying logistics. This paper explains the advantage of the EAD method and the rationale for selection of these two EAN mixtures to cover the spectrum of normal scuba working depths.

INTRODUCTION

Enriched Air Nitrox (EAN) diving is a technique used to compensate for the inherent increased decompression and decreased bottom times experienced at deeper scuba depths. EAN breathing mixtures always contain a lower fraction of nitrogen than air. The decrease in nitrogen lessens the intake load on the tissues and decompression time is subsequently reduced (Galerne, 1989). This reduction of decompression obligation for any EAN mixture can be calculated using the equivalent air depth (EAD) method. EAD is a procedure which distinguishes between a diver's physical and physiological depth. The diver breathing an EAN mixture at a specific depth realizes a nitrogen absorption rate equivalent to that at a lesser depth. Consequently, decompression is based not on the actual, but on the equivalent physiological depth of the dive (Dinsmore, 1988). Since decompression is also based on the calculated equivalent air depth (EAD), a shallower decompression table (*e.g.*, more "no-stop" bottom time) can normally be used.

The real advantage in bottom time using EAN occurs during repetitive dives. Because some bottom times are limited by oxygen exposure (see note at bottom of Table 1), it is important to use proper RNT's against the proper maximum no-stop times. Since the decompression requirement is based on the EAD of the repetitive dive, it is imperative to use the RNT table for the particular mixture to be used (air 21%, EAN 32% or 36%) during the repetitive dive. For example: the first dive was made breathing air and the second using 32% EAN, the RNT table for the 32% mixture must be used.

Divers breathing EAN mixtures are exposed to higher oxygen concentrations than that experienced with compressed air. Consequently, they must be closely monitored for

Table 1

36% EAN Mixture

PO_2	Actual Depth	E.A.D.	US Table (ft.)	B.T.* (mins)	PO_2	Actual Depth	E.A.D.	USN Table (ft.)	B.T.* (mins)
1.01	60	42.3	50	100	1.32	88	65.0	70	**50**
1.02	61	43.1	50	100	1.33	89	65.8	70	**50**
1.03	62	43.9	50	100	1.34	90	66.6	70	**50**
1.04	63	44.7	50	100	1.35	91	67.4	70	**50**
1.05	64	45.5	50	100	1.36	92	68.2	70	**50**
1.06	65	46.3	50	100	1.37	93	69.0	70	**50**
1.08	66	47.2	50	100	1.38	94	69.8	70	**50**
1.09	67	48.0	50	100	1.39	95	70.6	80	40
1.10	68	48.8	50	100	1.40	96	71.5	80	40
1.11	69	49.6	50	**80**	1.41	97	72.3	80	**40**
1.12	70	50.4	60	60	1.42	98	73.1	80	**40**
1.13	71	51.2	60	60	1.44	99	73.9	80	**40**
1.14	72	52.0	60	60	1.45	100	74.7	80	**40**
1.15	73	52.8	60	60	1.46	101	75.5	80	**40**
1.16	74	53.6	60	60	1.47	102	76.3	80	**40**
1.17	75	54.4	60	60	1.48	103	77.1	80	**40**
1.18	76	55.3	60	60	1.49	104	77.9	80	**40**
1.20	77	56.1	60	60	1.50	105	78.7	80	**40**
1.21	78	56.9	60	**60**	1.51	106	79.6	80	30
1.22	79	57.7	60	**60**	1.52	107	80.4	90	**30**
1.23	80	58.5	60	**60**	1.53	108	81.2	90	**30**
1.24	81	59.3	60	**60**	1.54	109	82.0	90	**30**
1.25	82	60.1	70	50	1.56	110	82.8	90	**30**
1.26	83	60.9	70	50	1.57	111	83.6	90	**30**
1.27	84	61.7	70	50	1.58	112	84.4	90	**30**
1.28	85	62.5	70	50	1.59	113	85.2	90	**30**
1.29	86	63.4	70	50	1.60	114	86.0	90	**30**
1.30	87	64.2	70	50					

*Note: Numbers listed in bold are based on PPO_2 time limits.
Unbolded numbers are based on USN no-decompression limits.
Underlined numbers are based on both PPO_2 time and no-decompression limits.

Table 2

36% EAN Mixture

Repetitive Dive Depth (fsw)

		58-69	70-81	82-94	95-106	107-118	119-131	132-143	144-155			
A	7	6	5	4	4	3	3	3	3	3	2	2
B	17	13	11	9	8	7	7	6	6	6	5	5
C	25	21	17	15	13	11	10	10	9	8	7	7
D	37	29	24	20	18	16	14	13	12	11	10	9
E	49	38	30	26	23	20	18	16	15	13	12	12
F	61	47	36	31	28	24	22	20	18	16	15	14
G	73	56	44	37	32	29	26	24	21	19	18	17
H	87	66	52	43	38	33	30	27	25	22	20	19
I	101	76	61	50	43	38	34	31	28	25	23	22
J	116	87	70	57	48	43	38	34	32	28	26	24
K	138	99	79	64	54	47	43	38	35	31	29	27
L	161	111	88	72	61	53	48	42	39	35	32	30
M	187	124	97	80	68	58	52	47	43	38	35	32
N	213	142	107	87	73	64	57	51	46	40	38	35
O	241	160	117	96	80	70	62	55	50	44	40	38
Z	257	169	122	100	84	73	64	57	52	46	42	40

any symptoms of CNS oxygen toxicity. By taking into account both CNS toxicity and decompression obligation for a specific depth/time combination, the "optimal" EAN mixture can be calculated. This optimal mixture allows the maximum decompression advantage without exceeding the accepted level of oxygen exposure (Wells, 1988). Once the optimal enriched air mixture for a planned dive profile has been identified, the EAD is calculated to determine the decompression table.

The calculation of EAD, partial pressure of oxygen (PPO_2), and optimal EAN mixture is a tedious and time consuming process in which mathematical errors can not be tolerated. To simplify operational use of EAD's and prevent mathematical errors, in 1987 NURC/UNCW developed a set of EAD diving tables that cover EAN mixtures from 30% to 40% oxygen at 1% increments (Dinsmore, 1988) Each table (see example Table 1) shows for each foot of depth: 1) PPO_2, 2) EAD, 3) USN decompression table, and 4) maximum no-stop bottom. A separate table is used to select the residual nitrogen penalty time (RNT) for each mixture, again using the USN diving tables. Table 2 lists the RNT's for a 36% EAN mixture by appropriate repetitive depth intervals, (based on EAD's) for the diver's letter designation prior to the start of a repetitive dive.

USE OF MULTIPLE EAN MIXTURES

The concept of custom mixing specific EAN mixtures for particular depth profiles in order achieve the maximum bottom time possible is quite valid. However, trying to provide up to ten (10) different mixtures while maintaining a quick turn around between dives is a logistical nightmare. Since it is not reasonable to have on hand a cascade storage bank of each EAN mixture which may be used, each cylinder must be individually mixed for the specific nitrogen/oxygen combination. Additionally, once the scuba cylinder has been mixed and analyzed, should it require additional oxygen to meet the desired proportion, the entire scuba cylinder must be drained and refilled. This effort takes time and is costly. As a result, unless operations are limited to two or at most three mixtures, the productivity of the scientists will be limited by the mixing and analyzation process.

SELECTION OF EAN MIXTURES

NOAA Nitrox I

NOAA Nitrox I (NNI), a 32% enriched air mixture, was developed as the best general purpose EAN mixture for use in the 30 to 130 fsw depth range.(Wells, 1988) Published in the 1979 edition of the NOAA Diving Manual as Appendix E, these tables have been used operationally with great success for approximately 10 years (Miller, 1979). They are identical in format and use to the USN Standard Air Decompression Tables and were calculated using the EAD concept within the format constraints of the USN tables (even 10 fsw increments).

The 32% EAN mixture was selected because it could be safely used to a depth of 130 fsw which: 1) was the maximum authorized depth for NOAA sanctioned diving operations, and 2) equaled a partial pressure of oxygen of 1.6 ATA which is the cutoff depth for normal oxygen exposures. Depths deeper than 130 fsw exceed this 1.6 ATA limit and are considered exceptional exposures. Therefore, the 140 fsw and 150 fsw NNI table depths are not for standard operational purposes; rather, their inclusion is per the standard convention of providing depths and exposure times beyond the expected operational limits. These are to be used only when depth and/or time are inadvertently exceeded or in case of an emergency. Unfortunately, some individuals have used these tables to their maximum depth limits without fully understanding the PPO_2 ramifications. If an exceptional exposure profile must be used, divemasters should be aware of a printing error in the original copy of the tables. This error shows a stop at 10 fsw for 11 (eleven) minutes for a 150 fsw/15 minute dive profile. This should be corrected to read as only a one (1) minute stop at 10 fsw.

NNI vs. EAD (32%)

Figure 1 compares the maximum allowable no-stop bottom times for USN Standard Air, NOAA Nitrox I, and 32% oxygen EAN using NURC/UNCW EAD tables. It is not surprising that bottom times using air are less than those available breathing 32% oxygen EAN mixtures. What is surprising is the fact that bottom times based on 32% oxygen using the EAD method, are greater for many depths than those of NNI also composed of 32% oxygen. The reason for the differences is construction of the NNI Tables which rounds EAD depths to the nearest ten (10) foot increments to conform to the USN format. For example, all depths between 71 and 80 feet are grouped into an 80 foot table for 50 minutes of no-stop time. When using the EAD tables and diving between 70 and 75 fsw (EAD of less than 60 fsw) a 60 minute no-stop bottom time is obtainable. This comparative advantage of EAD's is maintained to various degrees throughout the depth range of the tables but generally is greatest between 70-110 fsw with narrowing at the deeper depths.

Figure 1
Max Depth/Time for No-stop Dive
Comparison of Air, NNI, and 32% EAD

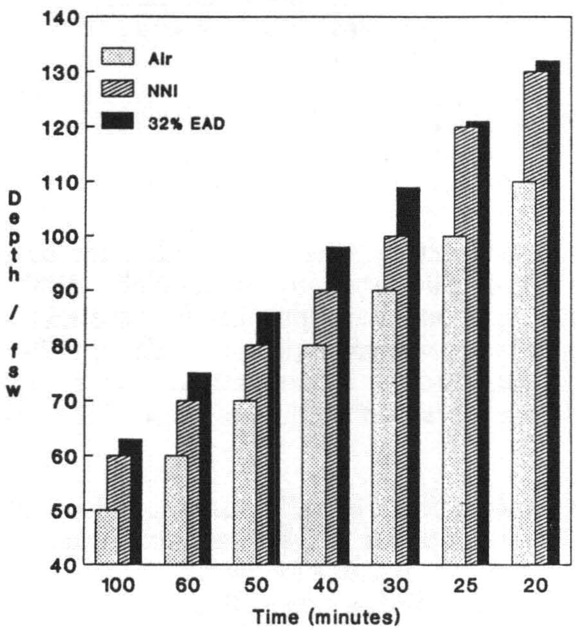
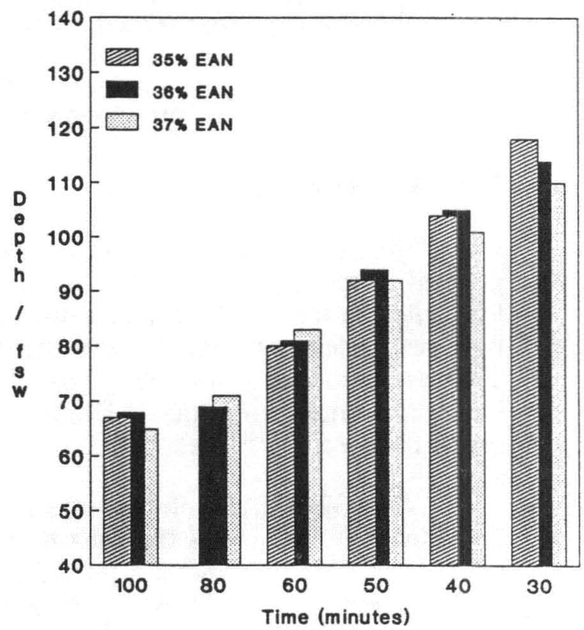


Figure 2
Max Depth/Time for No-Stop Dive
Comparison of 35, 36 and 37% EAN Mixture



36% Oxygen EAN

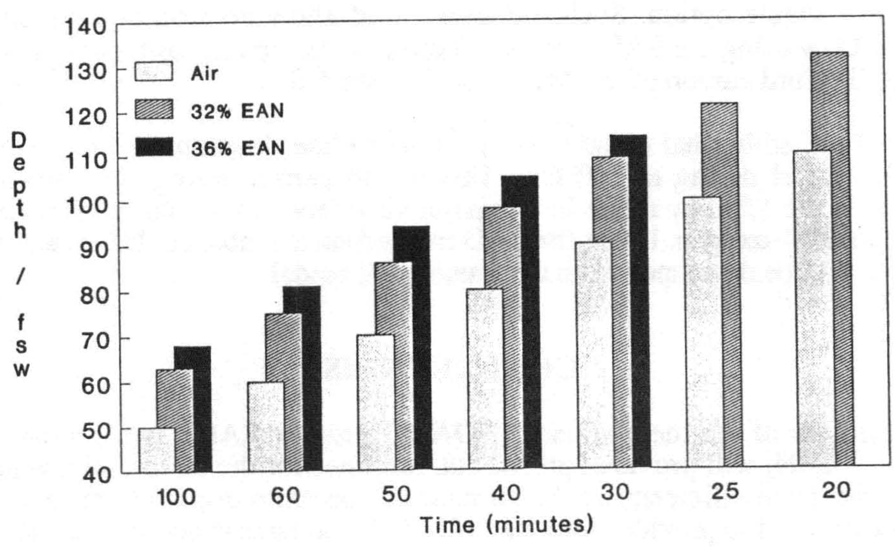
The selection of a "second-best all purpose" EAN mixture in support of field operations was based on the need to provide the maximum possible bottom times for scientists working in 60 to 110 fsw. NURC/UNCW has observed that many experiments are performed around depth-related stations, the most common of which are 60 and 100 fsw. Because of tidal change and other considerations, the 100 fsw site is normally somewhere between 95 and 105 fsw. The choices of EAN mixtures to best cover this depth range according to the N_2/O_2 Mixtures for Optimizing Dive Time Table (Dinsmore, 1988) are 35%, 36% or 37% oxygen mixtures. Comparison of the maximum no-stop bottom times of these three mixtures (Figure 2) shows that each has certain advantages over the others at various depth ranges. Generally, the 37% mixture is most advantageous in 70 - 84 fsw, 35% is unmatched in 115 - 118 fsw, and 36% is optimal in the 84 - 105 fsw depths.

NURC/UNCW's selection of 36% oxygen was based on two significant observations: 1) the ability to provide the greatest number of optimum bottom times throughout the 60 - 110 fsw range, and 2) the unmatched ability to provide 40 minutes of no-stop bottom time at 105 fsw.

OPERATIONAL CONSIDERATIONS

The use of two EAN mixtures greatly simplifies operational logistics. By limiting specific EAN mixtures to 32% and 36% oxygen, it is now feasible to have separate storage banks for each mixture for charging scuba cylinders more efficiently. NURC/UNCW's EAN system consists of an oil-less high pressure compressor with a constant mix system on line to a high pressure storage rack containing 24 cylinders (Wells, 1988). The cylinders are arranged in cascade banks composed of: 4 cylinders air, 4 cylinders 32% EAN, 8 cylinders 36% EAN, and 8 cylinders of oxygen for mixing (Mastro, 1989)

Figure 3. Max Depth/Time for no-stop dive. Operational mixtures used by NURC/UNCW.



Field operations conducted using these two primary mixtures must conform to the operational limits of the mixtures for partial pressure and decompression considerations. Since the maximum depth for a 36% oxygen mixture (based on a PPO_2 of 1.6 ATA) is 114 fsw, for planning purposes any dives 110 fsw or less will use 36% oxygen EAN. Dives planned between 110 - 130 fsw will use 32% oxygen EAN. The bottom time advantages of each mixture in relationship to depth is graphically displayed in Figure 3.

FUTURE ADVANCEMENTS IN EAN DIVING

Dr. J. Morgan Wells, NOAA Diving Coordinator and author of the NNI tables, is currently developing a second set of EAN tables to be designated NOAA Nitrox II (NNII). These tables will be designed to maximize bottom time to a depth of approximately 100 fsw. Dr. Wells' original concept was a set of tables like NNI that uses a 37.5% oxygen mixture (PPO_2 1.5 at 100 fsw) to provide an EAD equal to an 80 foot dive on USN tables. NURC/UNCW suggested that 36% EAN should be considered due to its operational advantages. Although it was agreed 36% was a more desirable mixture in the 60 - 100 fsw range, there were difficulties in fitting a 36% EAN mixture into 10-foot increment type tables using EAD calculations. This obstacle was recently overcome by the decision to use a physiological decompression model with the 36% mixture to develop the NNII tables. These tables will be similar in format to the NNI and USN tables, the differences being specific depth increments. The NOAA Nitrox II Tables should be calculated and tested this fall and available for distribution in early 1990.

Another anticipated enhancement in EAN diving is the extension of the partial pressure limits for oxygen breathing. Since all EAN diving is ultimately limited by these oxygen exposure guidelines, the extension of these values will have several implications: 1) when using present EAN mixtures, decompression obligation and not PPO_2 will be the primary limiting factor, 2) all tables such as NNI and NURC/UNCW's will need updating of allowable no-stop bottom times, 3) the concept of using higher percentages of EAN (greater than 40%) at moderate depths to lower the EAD and thus decompression obligation will become a viable option. Such mixtures could allow no-stop bottom times of 200 minutes at 60 fsw using the EAD method. These new oxygen exposure limits will soon be published in the third edition of the NOAA Diving Manual.

One final additional enhancement would be the development of EAN tables to support operational diving to 160 fsw. This would permit diving scientists to conduct experiments in the 150 fsw range in comparative safety and would require a mixture of approximately 28% oxygen. Using the EAD method such a table could be calculated, but a better table would be developed from a physiological model.

CONCLUSIONS

Regardless of the method used (NOAA Nitrox or EAD), two primary mixtures, 32% and 36% EAN, will provide optimal bottom times for the 60 to 130 fsw depth range with nearly the same efficiency of the 10 mixture spectrum originally proposed in 1988. The logistics required to provide more than two EAN mixtures is not practical and will limit operational productivity. Decompression tables, such as NNI that copy the format of USN Standard Air Tables, are recommended for those individuals and organizations not schooled in the EAD concept and its relationship to the PPO_2 exposure limits. Those diving professionals who have the need for every advantage a mixture can offer should consider the use of EAD tables such as those developed at NURC/UNCW.

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