International Conference KNOWLEDGE-BASED ORGANIZATION
Vol. XXI No 3 2015

OPTIMIZATION OF DIVING WITH "NITROX" OVER-OXYGENATED BREATHING MIXTURES, TO DEPTHS OF 15 ÷ 50 METRES

Mircea DEGERATU*, Simona RUS, Ana ION*****

***Technical University of Civil Engineering Bucharest, Romania,**
****Diving Center, Constanta, Romania,**
*****"Mircea cel Bătrân" Naval Academy of Constanta, Romania,**
degeratu.mircea@yahoo.com, simona_elena_rus@yahoo.com, ana_ion_ana@yahoo.ro

***Abstract**: The efficiency of diving activities carried out by divers should be increased. Improving the efficiency of interventions made with divers at depths greater than 15m has brought into focus the problem of increasing underwater working time by using over-oxygenated synthetic breathing mixtures in order to optimize the relation between working time and duration of decompression. The "NITROX" binary mixture best meets the requirements of diving at depths within the range of 15 to 50 meters. NITROX is used for depths in the range of 15 to 50 m. When this mixture is used, the decompression time shortens and the respiratory resistance decreases. Therefore, the use of NITROX leads to an improvement in diving efficiency, by increasing underwater working time, and by reducing the decompression time.*

Keywords: streamlining of divers interventions, binary synthetic breathing mixtures, immersion depth, diver‘s breath, inert gas.

1. Introduction

The efficiency of diving activities carried out by divers should be increased. Improvement of the efficiency of interventions with divers, at depths greater than 15m, have brought into focus the problem of increasing the underwater working time, by using over oxygenated synthetic breathing mixtures, in order to optimize the relation between working time and duration of decompression. The "NITROX" binary breathing mixture is the gas that best meets the requirements of diving at depths within the range of 15 to 50 meters.

The increased safety ensured by the over oxygenated synthetic breathing mixtures, which comprise inert nitrogen gas, drew attention to the need to further research on diving with NITROX, which proved to be superior to breathing mixtures with air.

2. Objectives

The main objectives of the study are:

- increasing of diving safety by reducing the decompression time;
- raising the divers' level of comfort by means of NITROX mixtures, which are superior to air mixtures since they use binary mixtures with nitrogen inert gas, which has a high partial oxygen pressure; the former types of mixtures have important consequences over divers' activity;
- increasing the diving efficiency as the ratio of underwater working time, and the amount of time necessary for diving, work and decompression; this is a fundamental desideratum for autonomous diving (for which the respiratory mixture reserve is limited) and for surface-supplied gas;

Therefore, we reiterate the main objective of this study: raising the efficiency of divers' interventions, to depths between 15 and 50 meters, using synthetic over-oxygenated breathing mixtures by means of nitrogen inert gas, which tends to reduce the ratio of effective working time, and the duration of decompression.

DOI: 10.1515/kbo-2015-0113

3. Case Study

For this study we took into consideration eight blends of NITROX mixtures, as follow: 60/40, 50/50, 40/60, 36/64, 32.5 / 67, 32/68, 30/70 and 28/72 (O2 [%] / N2 [%]).

As it can be observed, the concentration of O2 is higher than the concentration of O2 (21%) existing in air, and is between 28% and 60%.

The results of calculations were summarized in the tables below (figure 4, 5, 6, 7).

3.1. Generalities about air breathing mixtures

Normally, air is the gas used for diving in safe conditions, up to 57 meters.

Air is a natural breathing mixture. It has to be clean, dry and filtered; it does not have to contain any oil, water or other contaminants, above the levels required by professional standards.

If air is used as a breathing mixture at depths greater than 57 meters, divers' lives can be threatened; in returning to surface fatigue problems may arise. It is therefore necessary to adapt the level of decompression, i.e. to stop the diver at different depths levels, for a certain period of time, so as the body gradually can adapt to the atmospheric pressure (to reduce the remaining inert gas bubbles).

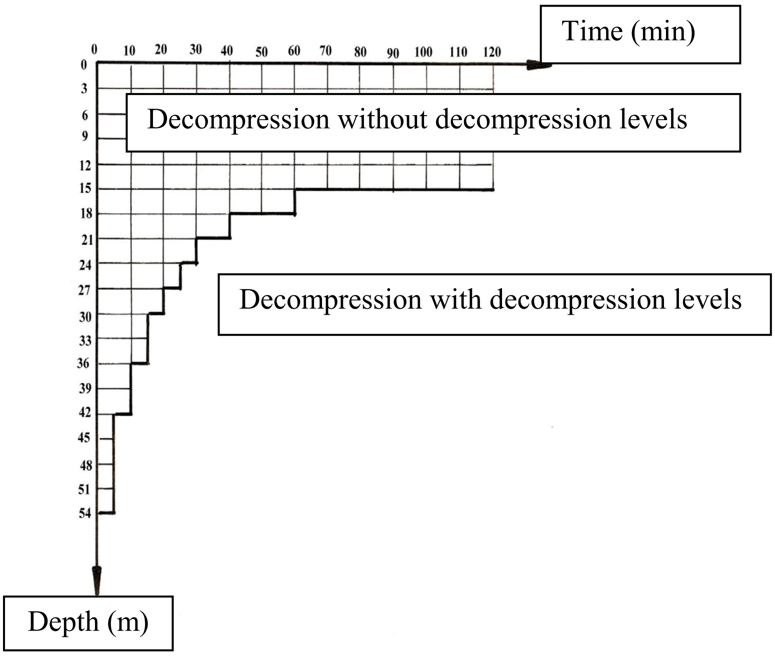


Figure 1: Use of diving air tables depending on depth and duration of dive

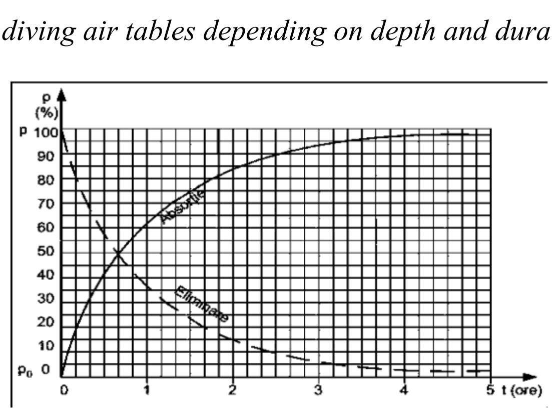


Figure 2: The theoretical curves of absorption and elimination of nitrogen from human tissue

This study intends to contribute to the improvement of diving efficiency by at least 10% (we are referring to the advantage of diving with NITROX over diving with air) using respiratory gas mixtures and specific NITROX decompression tables. Therefore, figure 2 [1, p. II-1] shows the theoretical curves of absorption and elimination of nitrogen from human tissue resulting from the tests.

Decompression is that stage of diving in which the diver returns to the atmospheric pressure.

It is the stage in which the reversible process of releasing the inert gas dissolved in the tissues (desaturation) and its elimination through the lungs takes place.

Desaturation, as can be seen in the figure above (figure 2), is an exponential function which is initiated when the diver starts to ascent towards the decompression site; the desaturation process is interrupted when the diver starts to breath normally.

The decompression speed is given by the rate of elimination of the inert gas dissolved in the body tissues during exposure to pressure.

Figure 3 [1, p. II-10] shows the variation of the partial pressure of inert gas according to time, in a tissue with saturation period H, during decompression in a period of time "t", measured in minutes, in accordance with the partial pressure of the inert gas P_{hgi}.

The desaturation curve is asymptotic to the partial pressure of inert gas, and it stops at a value $\leq$ to the maximum allowable voltage, P_{adm} of inert gas dissolved in the tissue.

In diving with binary over-oxygenated mixtures, a significant decrease in the time needed for diver's return to normal air is observed (table no. 1), as compared to the situation when compressed air is used.

Decompression time is calculated by adding the times for each level listed in the diving tables (irrespective of the mixture used, i.e. air or synthetic mixtures) usually used in the diving process, according to the breathing mixture.

Following this line, the present study will demonstrate that by replacing air with NITROX binary mixtures, at different depths and for different periods of time ($t_s = t_c + t_l$), the decompression stage (t_d) will be shorter, thus improving diving efficiency.

This approach represents a novelty in our country.

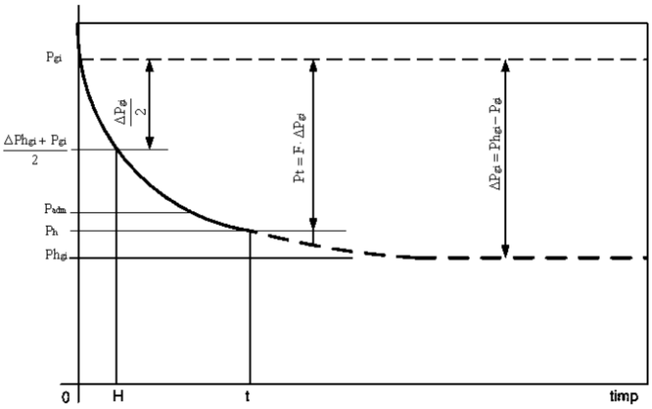


Figure3: Variation of the inert gas partial pressure in a H period tissue, during decompression, for a time "t" measured in minutes

Research has shown that this can stand true for certain diving depths and specific periods of immersion depths and can effectively use certain NITROX mixtures for other diving depths and durations.

3.2. Generalities about "NITROX" over-oxygenated breathing mixtures

The divers' gas cylinders are filled with NITROX (used only for this type of mixture); the maximum depth of immersion and the type of respiratory mixture is written on the cylinders. NITROX is used for depths in the range 15 to 50 m. By using this mixture, the decompression time shortens, and the respiratory resistance decreases.

Therefore, the use of NITROX leads to an improvement of diving efficiency, by increasing the underwater working time, and by reducing decompression.

The purpose of this paper is to study the ways of increasing diving efficiency by using NITROX binary mixtures.

For NITROX dives, special tables are used for decompression; the values in the tables correspond to a depth lower than the real depth; it is called equivalent depth, calculated by formula (1).

Divers can use autonomous open, closed, semi-closed and mixed-circuit devices.

The calculation formula for the equivalent depth is:

$$h_{ech} = h\frac{(p_{N2})_{am}}{(p_{N2})_{air}} \quad (1)$$

where: h_{ech} = equivalent depth, h = depth of immersion (m), $(p_{N2})_{am}$ = partial pressure of nitrogen in the breathing mixture (bar (sc. abs.)), $(p_{N2})_{air}$ = partial pressure of nitrogen in the air (bar (sc. abs.)).

The partial pressures of nitrogen in the breathing mixture and in the air are calculated with the following relations:

$$(p_{N2})_{am} = (r_{N2})_{am} \cdot p \quad (2)$$

$$(p_{N2})_{air} = (r_{N2})_{air} \cdot p \quad (3)$$

where, $(r_{N2})_{am}$ = the volumetric participation of N_2 in the breathing mixture, $(r_{N2})_{aer}$ = volumetric participation of N_2 in the air, p = the pressure corresponding to the depth of immersion [bar (abs. sc.)].

The researchers and engineers working in the CPSA Lab. and Hyperbaric Laboratory, belonging to the Diving Center, an also to the Technical University of Civil Engineering of Bucharest, among others, have made many attempts, over time, in the Hyperbaric Laboratory; here, leaving behind the old decompression process, which took into account the equivalent depth, they calculated specialized diving decompression tables for diving on "NITROX" type breathing mixtures, along with decompression tables for diving on NITROX mixtures under saturation, based on a calculation method similar to the method used to calculate decompression table after diving with compressed air. This new method is more efficient than the method that used the equivalent depth.

Table 1 [3, p. 113] shows a comparison between the over-oxygenated NITROX breathing binary gas mixtures and air during decompression periods.

These mixtures are considered over-oxygenated because O_2 has a higher concentration, i.e. 21% (O_2 in air).

Table 1 Comparison between over-oxygenated "NITROX" and air during decompression periods

100 minute diving at a depth of 30 meters				
Breathing mixture used for decompression	*Air*	*"NITROX" over-oxygenated breathing mixtures*		
		30% O_2	*40% O_2*	*50% O_2*
Total duration of decompression	88,4	45,6	20,8	2,8

A permanent care should be taken concerning the O_2 partial pressure; it should not exceed the toxicity limit.

The breathing mixture should be checked before each dive, so as to correspond to the depth planned; also, the dosage of the synthetic breathing mixture should be correctly adjusted. Using a wrong gas dosage can lead to hypoxya or hyperoxia, i.e. lack of oxygen, or intoxication with oxygen, which may endanger the divers' lives.

3.3. The study

The study involved conducting hundreds of calculations whose results were placed in tables, such as those in fig. 4, 5, 6, 7. They will briefly be presented in the paragraph below.

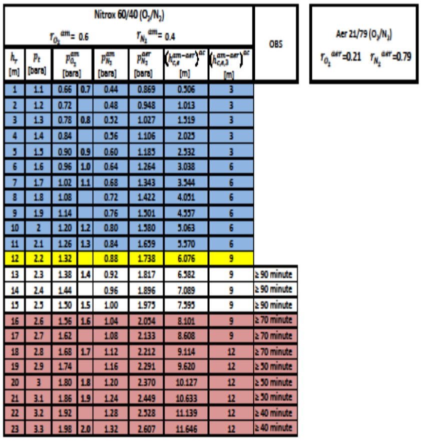
All research has focused on calculations regarding:

- deepest immersions,
- decompression times (regarding surface ascent) $t_r = t_d$ calculated for different NITROX mixtures, different depths h, and different times of immersion t_s,
- efficiency of diving with air η_s^{aer},
- efficiency of diving with NITROX mixtures $(\eta_s^{am})^{ac}$,
- determination of the values of efficiency $(\Delta\eta)^{ac}$ resulting from diving that used NITROX type over-oxygenated binary mixtures, as opposed to diving with air.

For the present case study 8 types of NITROX mixtures (O_2[%]/N_2[%]) were considered, as follow: 60/40, 50/50, 40/60, 36/64, 32.5 / 67.5, 32/68, 30/70 and 28/72.

Using approximate relationships, calculations were made for values of equivalent depths, at different depths of immersion. The results are summarized synthetically in tables 2.1 ÷ 2.8 (see figure 4 and 5).

Tabel 2.1



Nitrox 60/40 (O_2/N_2)

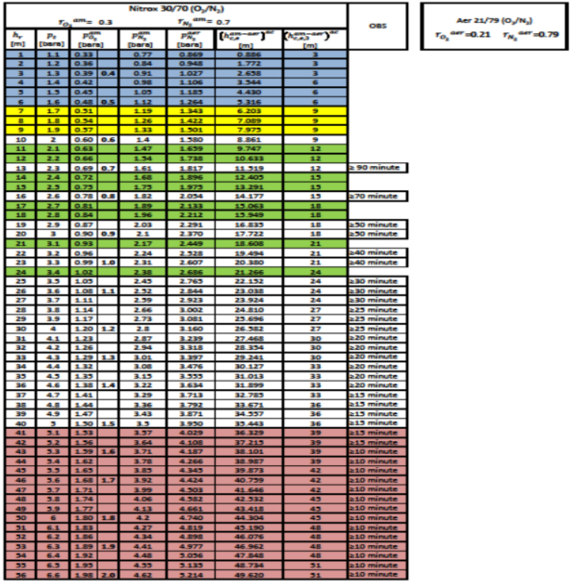
$r_{O_2}^{am}= 0.6$ $r_{N_2}^{am}= 0.4$

Aer 21/79 (O_2/N_2)

$r_{O_2}^{aer}=0.21$ $r_{N_2}^{aer}=0.79$

h_r [m]	p_t [bara]	$p_{O_2}^{am}$ [bara]		$p_{N_2}^{am}$ [bara]	$p_{N_2}^{aer}$ [bara]	$(h_{c,e}^{am-aer})^{ac}$ [m]	$(h_{c,e,3}^{am-aer})^{ac}$ [m]	OBS
1	1.1	0.66	0.7	0.44	0.869	0.506	3	
2	1.2	0.72		0.48	0.948	1.013	3	
3	1.3	0.78	0.8	0.52	1.027	1.519	3	
4	1.4	0.84		0.56	1.106	2.025	3	
5	1.5	0.90	0.9	0.60	1.185	2.532	3	
6	1.6	0.96	1.0	0.64	1.264	3.038	6	
7	1.7	1.02	1.1	0.68	1.343	3.544	6	
8	1.8	1.08		0.72	1.422	4.051	6	
9	1.9	1.14		0.76	1.501	4.557	6	
10	2	1.20	1.2	0.80	1.580	5.063	6	
11	2.1	1.26	1.3	0.84	1.659	5.570	6	
12	2.2	1.32		0.88	1.738	6.076	9	
13	2.3	1.38	1.4	0.92	1.817	6.582	9	≥ 90 minute
14	2.4	1.44		0.96	1.896	7.089	9	≥ 90 minute
15	2.5	1.50	1.5	1.00	1.975	7.595	9	≥ 90 minute
16	2.6	1.56	1.6	1.04	2.054	8.101	9	≥ 70 minute
17	2.7	1.62		1.08	2.133	8.608	9	≥ 70 minute
18	2.8	1.68	1.7	1.12	2.212	9.114	12	≥ 70 minute
19	2.9	1.74		1.16	2.291	9.620	12	≥ 50 minute
20	3	1.80	1.8	1.20	2.370	10.127	12	≥ 50 minute
21	3.1	1.86	1.9	1.24	2.449	10.633	12	≥ 50 minute
22	3.2	1.92		1.28	2.528	11.139	12	≥ 40 minute
23	3.3	1.98	2.0	1.32	2.607	11.646	12	≥ 40 minute

Tabel 2.7



Nitrox 30/70 (O_2/N_2)

$r_{O_2}^{am}= 0.3$ $r_{N_2}^{am}= 0.7$

Aer 21/79 (O_2/N_2)

$r_{O_2}^{aer}=0.21$ $r_{N_2}^{aer}=0.79$

h_r [m]	p_t [bara]	$p_{O_2}^{am}$ [bara]		$p_{N_2}^{am}$ [bara]	$p_{N_2}^{aer}$ [bara]	$(h_{c,e}^{am-aer})^{ac}$ [m]	$(h_{c,e,3}^{am-aer})^{ac}$ [m]	OBS
1	1.1	0.33		0.77	0.869	0.886	3	
2	1.2	0.36		0.84	0.948	1.772	3	
3	1.3	0.39	0.4	0.91	1.027	2.658	3	
4	1.4	0.42		0.98	1.106	3.544	6	
5	1.5	0.45		1.05	1.185	4.430	6	
6	1.6	0.48	0.5	1.12	1.264	5.316	6	
7	1.7	0.51		1.19	1.343	6.203	9	
8	1.8	0.54		1.26	1.422	7.089	9	
9	1.9	0.57		1.33	1.501	7.975	9	
10	2	0.60	0.6	1.4	1.580	8.861	9	
11	2.1	0.63		1.47	1.659	9.747	12	
12	2.2	0.66		1.54	1.738	10.633	12	
13	2.3	0.69	0.7	1.61	1.817	11.519	12	≥ 90 minute
14	2.4	0.72		1.68	1.896	12.405	15	
15	2.5	0.75		1.75	1.975	13.291	15	
16	2.6	0.78	0.8	1.82	2.054	14.177	15	≥70 minute
17	2.7	0.81		1.89	2.133	15.063	18	
18	2.8	0.84		1.96	2.212	15.949	18	
19	2.9	0.87		2.03	2.291	16.835	18	≥50 minute
20	3	0.90	0.9	2.1	2.370	17.722	18	≥50 minute
21	3.1	0.93		2.17	2.449	18.608	21	
22	3.2	0.96		2.24	2.528	19.494	21	≥40 minute
23	3.3	0.99	1.0	2.31	2.607	20.380	21	≥40 minute
24	3.4	1.02		2.38	2.686	21.266	24	
25	3.5	1.05		2.45	2.765	22.152	24	≥30 minute
26	3.6	1.08	1.1	2.52	2.844	23.038	24	≥30 minute
27	3.7	1.11		2.59	2.923	23.924	24	≥30 minute
28	3.8	1.14		2.66	3.002	24.810	27	≥25 minute
29	3.9	1.17		2.73	3.081	25.696	27	≥25 minute
30	4	1.20	1.2	2.8	3.160	26.582	27	≥25 minute
31	4.1	1.23		2.87	3.239	27.468	30	≥20 minute
32	4.2	1.26		2.94	3.318	28.354	30	≥20 minute
33	4.3	1.29	1.3	3.01	3.397	29.241	30	≥20 minute
34	4.4	1.32		3.08	3.476	30.127	33	≥20 minute
35	4.5	1.35		3.15	3.555	31.013	33	≥20 minute
36	4.6	1.38	1.4	3.22	3.634	31.899	33	≥20 minute
37	4.7	1.41		3.29	3.713	32.785	33	≥15 minute
38	4.8	1.44		3.36	3.792	33.671	36	≥15 minute
39	4.9	1.47		3.43	3.871	34.557	36	≥15 minute
40	5	1.50	1.5	3.5	3.950	35.443	36	≥15 minute
41	5.1	1.53		3.57	4.029	36.329	39	≥15 minute
42	5.2	1.56		3.64	4.108	37.215	39	≥15 minute
43	5.3	1.59	1.6	3.71	4.187	38.101	39	≥10 minute
44	5.4	1.62		3.78	4.266	38.987	39	≥10 minute
45	5.5	1.65		3.85	4.345	39.873	42	≥10 minute
46	5.6	1.68	1.7	3.92	4.424	40.759	42	≥10 minute
47	5.7	1.71		3.99	4.503	41.646	42	≥10 minute
48	5.8	1.74		4.06	4.582	42.532	45	≥10 minute
49	5.9	1.77		4.13	4.661	43.418	45	≥10 minute
50	6	1.80	1.8	4.2	4.740	44.304	45	≥10 minute
51	6.1	1.83		4.27	4.819	45.190	48	≥10 minute
52	6.2	1.86		4.34	4.898	46.076	48	≥10 minute
53	6.3	1.89	1.9	4.41	4.977	46.962	48	≥10 minute
54	6.4	1.92		4.48	5.056	47.848	48	≥10 minute
55	6.5	1.95		4.55	5.135	48.734	51	≥10 minute
56	6.6	1.98	2.0	4.62	5.214	49.620	51	≥10 minute

Figure 4 and 5: Calculation of the values of equivalent depths, for different depths of immersion

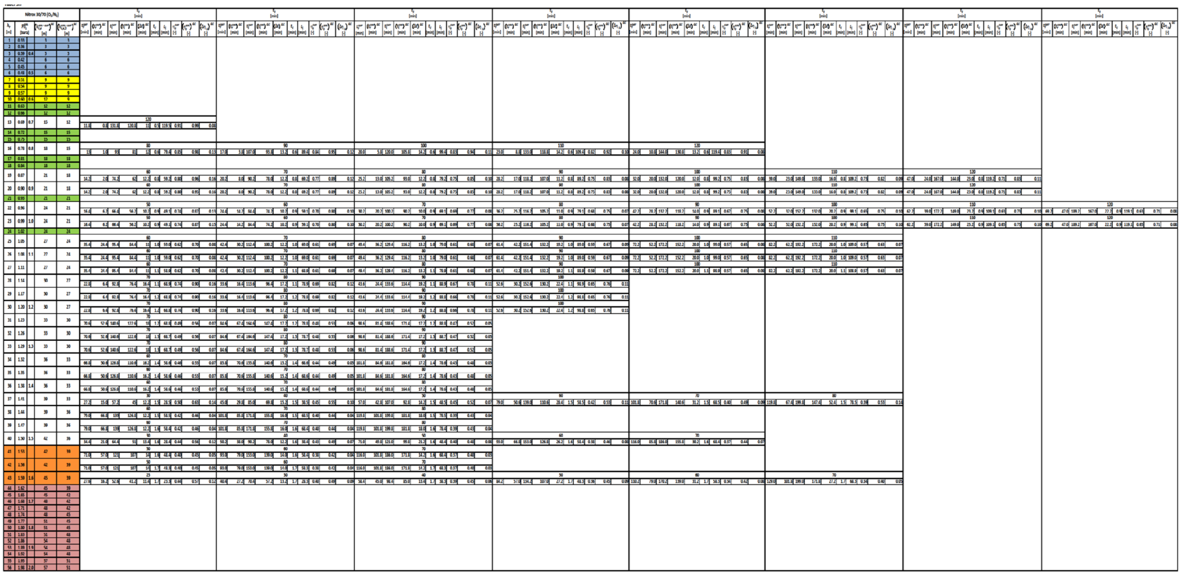


Figure 6: Calculation of the efficiency of diving for different immersion depths

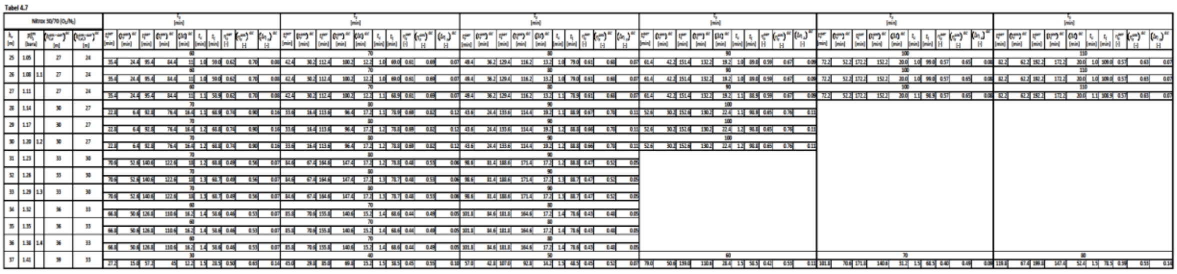


Figure 7: Optimization of diving efficiency (see and figure 6)

In the case of diving with open-circuit breathing apparatus, using NITROX type over-oxygenated binary mixtures, the recommended maximum partial pressure of oxygen in the mixture, p_{O2max}, should be between 1.4 and 1.6 bar; the value of 1, 4 bar is recommended for amateur diving.

In our application, for professional diving, the upper limit of oxygen partial pressure $p_{O_2}^{\max}$ = 1,5 bara was selected (toxicity limit). For this value table 2 shows the maximum depth of immersion h_{max} for different NITROX type breathing mixtures.

Table 2 The maximum depth for diving with different "NITROX" types mixtures

The maximum depth h_{max} [m] for $p_{O_2}^{\max}$ = 1.5 bara (bara = bar in absolute scale)						
NITROX (O_2 / N_2)						
50 / 50	*40 / 60*	*36 / 64*	*32.5 / 67.5*	*32 / 68*	*30 / 70*	*28 / 72*
20	*27*	*31*	*36*	*36*	*40*	*43*

In this paper, the method of the equivalent depth was used, and initially, the depth correction calculation based on an approximate relation was made; after that, the depth corrections were also carried out with a real calculation relation.

To calculate the tables through the equivalent depth method, we started from the tables (LH82) for diving with air; the calculation was carried out in the Hyperbaric Laboratory; such calculations are common activities of the Diving Center.

As aforementioned, this approach is new, its result showing that a special type of NITROX mixture will be used for diving at certain depths, while for the other ranges of diving and duration, compressed air will be used.

The approximate calculus relations are:

$$(h_{c,e}^{am-aer})^{ac} = h \cdot \frac{p_{N_2}^{am}}{p_{N_2}^{aer}} \tag{4}$$

$$(h_{c,e,3}^{am-aer})^{ac} = (h_{c,e}^{am-aer})^{ac} + (0...3) \tag{5}$$

The calculus relations are:

$$(\eta_s^{am})^{ac} = \frac{t_l}{(t_t^{am})^{ac}}, \tag{6}$$

$$\eta_s^{aer} = \frac{t_l}{t_t^{aer}}, \tag{7}$$

$$(\Delta\eta)^{ac} = (\eta_s^{am})^{ac} - \eta_s^{aer}. \tag{8}$$

3.4. Optimization of diving activities using NITROX type breathing mixtures

The study involved conducting hundreds of calculations and placing the results in tables such as those presented in figure 4, 5, 6 and 7.

Starting from the tables 3.7 simplifications were made with the aim of increasing the efficiency of diving with NITROX binary mixtures, for different depths of immersion, and there has resulted figure 7 (shown in the above 4.7 table) as a synthesis on $(\Delta\eta_s)^{ac}$

optimization.

What we had in view throughout the study was the partial pressure of oxygen in NITROX type mixtures; the pressure was not allowed to exceed 1.5 bar (toxicity limit - see § 3.3), and the total dive time (t_t) was not allowed to exceed the time limit exposure to different oxygen partial pressures in NITROX breathing mixtures. The O_2 partial pressure of 1.5 bar did not exceed 1,5 bar; this value was considered when the specific calculations were made for professional divers'.

From tables 3.1 ÷ 3.8 simplifications were made, having in view the increase of the efficiency of diving with NITROX type binary mixtures, for different depths of immersion. The result (on $\Delta\eta_s$ optimization) can be seen in synthesis table (these tables are not presented in present paper).

What the authors have had in view throughout the study was that the partial pressure of the oxygen in the NITROX type mixtures be no higher than 1.5 bar (see § 3.2) and the total diving time (t_t) not exceed the exposure time limit to different oxygen partial pressures of the oxygen contained in the NITROX type breathing mixtures. The partial pressure of O_2 did not exceed the value of 1.5 bar, which is the reference value taken into consideration in professional divers underwater work.

4. Comments and conclusions

New opportunities have been revealed with regard to immersion, which led to the desire of a continuous improvement of techniques in diving activities. This paper has established at what depths and underwater working time can this method of using NITROX type breathing apparatus be applied for open circuit diving apparatus, so that the diving efficiency can have a significant effect.

The present study focused on the calculation of the diving depth limit, of decompression time ($t_d = t_r$) calculated for air, and for the eight types of NITROX binary mixtures studied, for different working depths (h), as well as for different immersion times $t_{s,}$ so as to determine a significant increase of diving.

In the end, we determined the values of the increase in efficiency $(\Delta\eta)^{ac}$ resulting from the unitary diving with open - circuit breathing apparatuses that used synthetic, binary, and over-oxygenated breathing mixtures, of NITROX type, against the use of compressed air as a natural breathing mixture. For this, the efficiency of diving with air η_s^{aer} , along with that of diving with NITROX type binary mixtures $(\eta_s^{am})^{ac}$ were calculated; all these results were shown in tables, devised for this purpose (see figure 7). These tables showed what types of diving would increase the efficiency by at least 8%. The results of all these calculations were noted in tables, and summarized in the paper's figures 4, 5, 6, and 7.

Bibliography

[1] Degeratu, Mircea, Petru, Aron, Georgescu, Ştefan, Ioniţă, Sergiu, *Tehnologii hiperbare pentru scufundări unitare şi în saturaţie*, MATRIX ROM Publishing House, Bucharest, 2008.

[2] *Manualul de Instruţie al Scafandrului*, FN 22/6, 2010.

[3] Norme privind pregătirea, organizarea şi protecţia muncii în activitatea de scufundare, FN 1995, published by the General Staff of the Navy, in *Official Gazette*, MO no. 272 from 23.11.1995.

[4] Petru, Aron, Degeratu, Mircea, Ioniţă, Sergiu, *Ghidul scafandrului autonom*, OLIMP PRESS Publishing House, Bucharest, 1992.