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NAVY EXPERIMENTAL DIVING UNIT
REPORT NO. 5-86

CENTRAL NERVOUS SYSTEM OXYGEN TOXICITY IN CLOSED-CIRCUIT SCUBA DIVERS III

By

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NAVY EXPERIMENTAL DIVING UNIT

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407

IN REPLY REFER TO:

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March 1986

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NEDU REPORT NO. 5-86	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CENTRAL NERVOUS SYSTEM OXYGEN TOXICITY IN CLOSED-CIRCUIT SCUBA DIVERS III		5. TYPE OF REPORT & PERIOD COVERED FINAL 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) LCDR F. K. BUTLER, Jr., MC, USN		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS NAVY EXPERIMENTAL DIVING UNIT PANAMA CITY, FL 32407-5001		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE MARCH 1986 13. NUMBER OF PAGES 52
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

OXYGEN TOXICITY	CLOSED-CIRCUIT OXYGEN DIVING
DRAEGER LAR V	OXYGEN DIVING
CNS OXYGEN TOXICITY	OXYGEN TOLERANCE TEST
PULMONARY OXYGEN TOXICITY	TEST PLAN #85-32
OXYGEN EXPOSURE LIMITS	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The U.S. Navy is currently interested in expanding its closed-circuit oxygen diving capabilities. Previous dive series at NEDU in 1982 and 1983 resulted in significant extensions of the oxygen exposure limits and the development of the transit/excursion concept in which a single excursion below 20 FSW is allowed during a four hour exposure providing the rest of the dive is spent at 20 FSW or shallower. This dive series was conducted in November/December 1985 and was designed to explore the possibility of doing

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (CONTINUED)

multiple downward excursion on a closed-circuit oxygen dive. One hundred fifty three experimental oxygen exposures of up to four hours were conducted in the Ocean Simulation Facility. Conclusions from this study were:

(1) Increasing the time at 20 FSW between downward excursions from 30 minutes to 60 minutes reduced the incidence of serious toxicity episodes from 14% to 5%. A 90 minute transit time eliminated toxicity episodes on subsequent excursions, but the number of dives on this profile was small.

(2) An initial excursion to 40 FSW for 15 minutes rendered divers susceptible to subsequent oxygen toxicity at 20 FSW. This effect is lessened, but not eliminated, by discounting the toxicity episodes at 20 FSW encountered by the oxygen sensitive divers in the study.

(3) No multiple excursion options are recommended at this time, but the 1984 oxygen exposure limits should continue to be used as previously published.

(4) The U.S. Navy standard Oxygen Tolerance Test was not sensitive enough to produce symptoms in the three oxygen-susceptible divers identified in this dive series. Extensions of the current limits and multiple downward excursions will probably not be feasible until a more sensitive method of identifying oxygen sensitive individuals is found.

(5) Minor symptoms of pulmonary oxygen toxicity were noted after some of the four hour dives. A maximum of four hours oxygen time per twenty-four hour period is recommended for closed-circuit oxygen diving operations.

ABSTRACT

The U.S. Navy is currently interested in expanding its closed-circuit oxygen diving capabilities. Previous dive series at NEDU in 1982 and 1983 resulted in significant extensions of the oxygen exposure limits and the development of the transit/excursion concept in which a single excursion below 20 FSW is allowed during a four hour exposure providing the rest of the dive is spent at 20 FSW or shallower. This dive series was conducted in November/December 1985 and was designed to explore the possibility of doing multiple downward excursions on a closed-circuit oxygen dive. One hundred fifty three experimental oxygen exposures of up to four hours were conducted in the Ocean Simulation Facility. Conclusions from this study were:

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KEY WORDS:
OXYGEN TOXICITY
DRAEGER LAR V
CNS OXYGEN TOXICITY
PULMONARY OXYGEN TOXICITY
OXYGEN EXPOSURE LIMITS
CLOSED-CIRCUIT OXYGEN DIVING
OXYGEN DIVING
OXYGEN TOLERANCE TEST
TEST PLAN #85-32

INTRODUCTION

The U.S. Navy is currently interested in expanding its closed-circuit oxygen diving capabilities. Previous dive series at NEDU in 1982 and 1983 resulted in significant advances in oxygen diving: single depth oxygen exposure limits were extended at most depths with some increases as much as 320% over the previous limits; a 50 foot capability was established; transit/excursion limits were established which allow for brief excursions as deep as 50 FSW during a dive of up to four hours providing the rest of the dive is spent at 20 FSW or shallower; a new purging procedure for the Draeger LAR V was established which uses less oxygen and is more tactical than the previous procedure; and finally, new information regarding the sensitivity of the standard Navy oxygen tolerance test was obtained. These studies[1,2,3] were essential in developing the new oxygen diving procedures[4] recently approved for U.S. Navy use (NEDU Report 7-85). A summary of the new oxygen exposure limits is shown in Figure 1. The current study was designed to investigate the possibility of making multiple downward excursions from 20 FSW and to establish the minimum time at 20 FSW or shallower necessary to allow these additional downward excursions to be made without an increased risk of Central Nervous System (CNS) oxygen toxicity.

METHODS

Diver-Subjects

Diver subjects were U.S. Navy divers stationed at the U.S. Navy Experimental Diving Unit or on temporary duty from Fleet Special Warfare commands. In addition, one diver each from the U.S. Army Special Forces and the Special Boat Squadron of the Royal Marines (United Kingdom) participated in the study. A total of 48 individuals participated and their physical characteristics are given in Table 1. The Draeger LAR V closed-circuit oxygen Underwater Breathing Apparatus (UBA) [Draegerwerk, Lubeck, Germany] was used for all studies. All divers were made familiar with the operation of the LAR V and were thoroughly briefed on recognition of the signs and symptoms of CNS oxygen toxicity. Training dives were conducted prior to beginning the experimental dives and emergency procedures were thoroughly rehearsed.

Apparatus, Measurements, and Conditions

All dives in this study were conducted in the Navy Experimental Diving Unit's Ocean Simulation Facility (OSF) complex in Panama City, FL. The overall dimensions of the cylindrical wet chamber are 47 feet (length) by 15 feet (internal diameter). For this dive series, a special platform 14 feet by 25 feet was constructed and placed in the wet chamber such that the platform was 4½ feet below the water surface. Four electrically braked pedal mode ergometers[5] on specially built frames were mounted on the platform which

FIGURE 1

U.S. NAVY OXYGEN EXPOSURE LIMITS

1984

1. Transit with Excursion Limits

TRANSIT - 20 FSW for 240 Minutes

EXCURSIONS:

21 to 40 FSW - 15 Minutes

41 to 50 FSW - 5 Minutes

1. Single Depth Exposure Limits

25 FSW or Shallower	-	240 Minutes
30 FSW	-	80 Minutes
35 FSW	-	25 Minutes
40 FSW	-	15 Minutes
50 FSW	-	10 Minutes

TABLE 1

Diver Physical Characteristics

Diver No.	Height (cm)	Weight (kg)	Age	Diver No.	Height (cm)	Weight (kg)	Age
1	188	94	36	28	183	97	36
2	178	86	39	29	175	80	25
3	185	92	44	30	173	80	33
4	193	86	36	31	188	84	26
5	175	68	38	32	179	73	29
6	162	54	35	33	184	91	32
7	196	86	31	34	168	66	25
8	180	87	43	35	170	75	23
9	180	83	34	36	178	77	25
10	180	67	31	37	177	82	24
11	183	91	34	38	180	75	26
12	183	80	30	39	168	71	21
13	175	80	36	40	188	90	24
14	175	86	30	41	185	86	22
15	190	89	31	42	178	88	21
16	179	75	27	43	178	86	23
17	180	89	29	44	183	91	24
18	168	73	29	45	175	76	21
19	183	70	25	46	171	65	21
20	183	94	25	47	173	78	21
21	188	89	25	4[illegible]	170	70	20
22	180	86	35				
23	170	84	39	Mean	179.0	81.0	29.7
24	193	93	32	Std.Dev.	7.4	9.5	6.4
25	168	68	39				
26	178	84	38				
27	173	71	32				

allowed the diver to pedal in the prone position approximately 1 FSW below the surface of the water. The shallow depth of the diver in the water column minimized the possibility of a gas embolism in the event of an underwater convulsion and allowed the diver to get his head out of the water simply by standing up. Profile depth was established by pressurizing the OSF to 1 foot shallower than the required depth, the water column of 1 foot establishing the correct depth relative to the midline of a prone diver. All dive subjects wore safety harnesses which could be snapped into an overhead safety hoist to facilitate safe evacuation from the wet chamber in the event of a convulsion or a severe oxygen toxicity episode.

The Draeger LAR V is a relatively simple closed circuit oxygen UBA consisting of a breathing bag connected to an inhalation hose with a CO_2 absorbent canister between the exhalation hose and the breathing bag (Fig. 2). Oxygen is added to the breathing bag automatically by a demand valve actuated when the bag collapses on inhalation or manually through a bypass valve.

Draeger LAR V UBAs with standard mouthpieces had a 1 foot gas sample line installed in the carbon dioxide canister effluent coupling terminating in a quick-disconnect fitting. Upon entering the chamber, divers connected the UBA sample line to a 0.125 inch internal diameter chamber sample line which routed the canister effluent sample to either a Perkin Elmer MGA 1100 (Perkin Elmer Aerospace Division, Pomona, CA) or Chemetron Medspect 2 (Chemetron Medical Products, St. Louis, MO) mass spectrometer. Gas samples were taken continuously at a flow rate of 200 cc/min surface volume. The sample line was approximately 100 feet long with a sample delay time of 30-45 seconds at the flow rate used. Oxygen and carbon dioxide levels were recorded every 30 seconds by an HP-1000 Computer (Hewlett Packard, Cupertino, CA) and monitored on a display.

Water temperature was maintained at 21.7°C (71°F) ± 1°F for the dive series and the divers were allowed to wear wetsuit tops or "shorty" wet suits (1/8" or 3/16" thickness). This temperature/thermal protection combination was designed to produce a core temperature decline of approximately 0.25°C per hour. On the four hour dives, diver core temperature was continuously monitored using a YSI 702-A rectal probe (Yellow Springs Instrumentation, Yellow Springs, OH). The dive was terminated if the diver's core temperature dropped below 35°C (95°F) provided it had dropped at least 2°C from pre-dive baseline.

Experimental Profiles and Procedures

The experimental profiles dove in this series were of two types; Multiple Excursion Profiles and Single Excursion Profiles. The Multiple Excursion Profiles consisted of excursions to 40 FSW for 15 minutes separated by a period at 20 FSW of varying lengths. The periods at 20 FSW were designated "Transit" periods and were adjusted during the series to try to find the minimum transit time such that additional excursions could be made

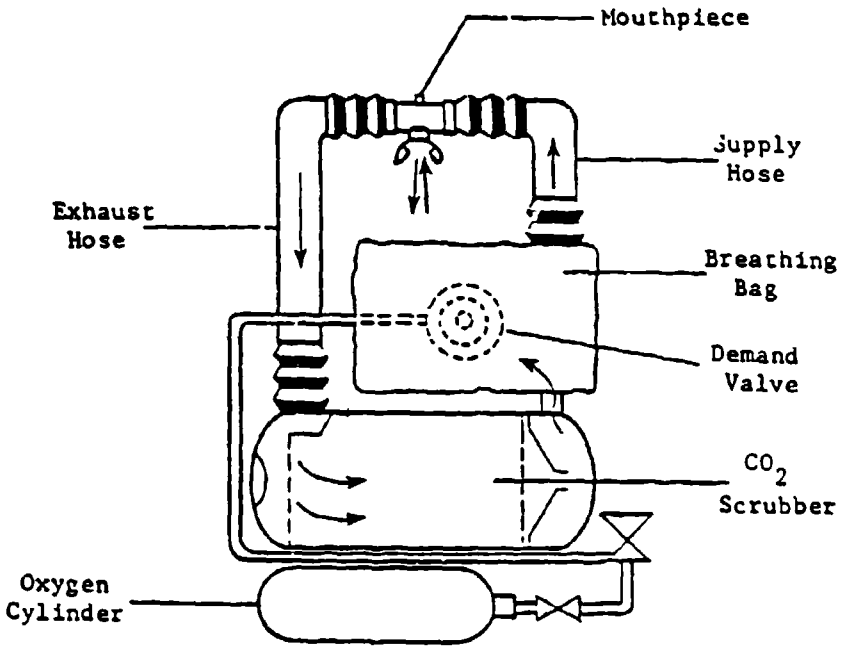

FIGURE 2. GAS FLOW PATH OF THE DRAEGER LAR V.

without increasing the likelihood of oxygen toxicity on the subsequent excursions. The profiles were designated by a two number title: the first number corresponds to the number of excursions to be done and the second number refers to length of the transit time at 20 FSW. The initial profile was thus designated 2-30: two excursions to 40 FSW separated by a 30 minute period at 20 FSW. Subsequent transit times were to be adjusted as necessary to enable a second excursion to be taken safely. Once the appropriate transit interval had been determined, additional excursions were to be added to the profiles. One profile (3-90) had a 15 minute period at 20 FSW following the third excursion to 40 FSW in order to achieve the desired 240 minute total dive time.

Three single excursion profiles were tested. Profile 40S-15 and 40S-15(M) consisted of one excursion to 40 FSW for 15 minutes at the Start of the dive followed by 225 minutes at 20 FSW. Profile 40M-15 consisted of a two hour exposure at 20 FSW followed by a 15 minute excursion to 40 FSW in the Middle of the dive and then a 105 minute exposure at 20 FSW. All single excursion dives had a total dive time of 240 minutes. The depths and times for all experimental profiles are presented in Table 2.

Four dive subjects were present on each dive. Prior to the dive, a "purge" procedure consisting of filling the breathing bag with oxygen and emptying it by exhaling to atmosphere a total of 3 times was performed. Divers then discontinued breathing from the UBA and entered the wet chamber. The monitoring umbilical was connected and the divers were compressed to depth standing on the platform with their head out of the water breathing chamber air. At depth, divers performed an additional purge procedure. These 2 purges were generally sufficient to achieve the desired inspired oxygen fraction of 95% as monitored on the mass spectrometer. The minimum oxygen fraction of 95% was chosen as a reasonable "worst case" condition for oxygen fraction[3]. Only after all divers had completed their purges and were ready to begin exercising on the ergometers was profile time begun. Additionally, the 15 minute excursion time did not include the ascent time back to 20 FSW. Thus, the period of oxygen breathing deeper than 20 FSW was generally 2 to 3 minutes in excess of the time shown on the profiles. During the study, the diver's inspired O_2 was monitored continuously and additional purges were done if a diver's inspired oxygen fraction fell below 95%.

The divers exercised continuously on the bicycle ergometer at 50 watts throughout the fifteen minute excursion. At the end of fifteen minutes, the divers were directed to stop work, and travel to 20 FSW was begun immediately. Travel time was generally 30-60 seconds and was included in the transit period. During the transit periods the divers performed 4 minute/6 minute rest/work cycles. The exercise rate was designed to approximate that of an underwater swimmer swimming at a comfortable rate (0.8 knots) which results in an oxygen consumption of approximately 1.3 liters/min[6]. Approximately one minute before the end of the designated transit time, the divers began travel back to 40 FSW for the next excursion. Compression time to 40 FSW was generally also 40-60 seconds. A maximum error of ± 30 seconds

TABLE 2

EXPERIMENTAL PROFILES

Profile Designation	Depth/Time
2-30	15 Minutes at 40 FSW
	30 Minutes at 20 FSW
	15 Minutes at 40 FSW
2-45	15 Minutes at 40 FSW
	45 Minutes at 20 FSW
	15 Minutes at 40 FSW
2-60	15 Minutes at 40 FSW
	60 Minutes at 20 FSW
	15 Minutes at 40 FSW
3-90	15 Minutes at 40 FSW
	90 Minutes at 20 FSW
	15 Minutes at 40 FSW
	90 Minutes at 20 FSW
	15 Minutes at 40 FSW
	15 Minutes at 20 FSW
40 M-15	120 Minutes at 20 FSW
	15 Minutes at 40 FSW
	105 Minutes at 20 FSW
40 S-15 and 40 S-15(M)	15 Minutes at 40 FSW
	225 Minutes at 20 FSW

from the designated transit time was allowed. Upon arrival at 40 FSW, the divers were directed to start work and the next 15 minute excursion was begun. The above sequence was repeated until the desired number of excursions and transit periods were accomplished.

Each Diver-Subject was monitored at all times by his own tender, who was positioned immediately adjacent to the diver. In addition, a standby diver equipped with air SCUBA gear was present in the wet chamber; a diving corpsman and safety hoist operator were present at depth in the dry trunk immediately above the wet chamber, and an NEDU Diving Medical Officer was present outside the chamber at all times during the dives.

All personnel in the wet chamber had been thoroughly briefed on the recognition of the signs and symptoms of CNS oxygen toxicity. Divers continued on the prescribed exercise protocol until symptoms consistent with CNS oxygen toxicity were observed either by the diver himself or his tender or until the profile was finished.

A spare UBA for each diver was prepared. If canister effluent CO_2, (as monitored by the mass spectrometer) exceeded 0.5% Surface Equivalent Value (SEV) (3.8 mmHg) for 2 continuous minutes or 1.0% SEV (7.6 mmHg) at any time or if oxygen bottle pressure dropped below 500 psi, the diver was directed to change his UBA during a rest period. UBA changes were designed to avoid any significant drop in oxygen partial pressure. The diver continued breathing from a UBA throughout, holding his breath as he switched from the expended UBA to the second UBA. The constant monitoring of CO_2 eliminated the possibility of a significant increase in inspired CO_2, which has been shown to potentiate CNS oxygen toxicity[7,8,9].

Modified Profile 40S-15

For reasons which will be described in the Results section, it became necessary to modify the experimental procedures significantly for some of the exposures on Profile 40S-15. Dives done using these procedures will be referred to as Profile 40S-15(M). The experimental conditions for these dives were identical to those described previously except as listed below:

(1) Divers did not purge their rigs prior to entering the chamber.

(2) Once all divers were standing by their ergometers and were ready to begin, they were directed to purge their rigs using the purge procedure shown in Figure 3. The fifteen minute excursion time was considered to begin at this point.

(3) Once the divers had completed their purges, which generally took 30-60 seconds, they assumed their positions on their ergometers. When all divers were finished purging, they were directed to begin work and the complex was pressed to 40 FSW.

(4) The divers continued to exercise during compression to 40 FSW which took 60-90 seconds. The travel time was also included in the 15 minute excursion time.

FIGURE 3

DRAEGER LAR V PURGE PROCEDURE FOR PROFILE 40S-15 (M)

(1) Ensure that the oxygen supply valve is closed. Blow all air out of lungs and insert mouthpiece. Open the dive/surface valve. (The dive/surface valve is left open for the remainder of the procedure).

(2) Empty air out of the breathing bag by inhaling from the mouthpiece and exhaling into the atmosphere (through the nose). Continue until the bag is completely empty.

NOTE

Be sure <u>not</u> to exhale into the mouthpiece (breathing bag) during the emptying process in step 3 or 5.

(3) Open the oxygen supply valve and fill the breathing bag by depressing the bypass valve completely for approximately 6 seconds. (The oxygen supply valve is left open for the remainder of the procedure.)

(4) Empty the breathing bag once more as in step 2.

(5) Fill the breathing bag to a comfortable volume for swimming by depressing the bypass valve completely for approximately 4 seconds. Begin normal breathing.

(5) The complex remained at 40 FSW until 14 minutes had elapsed and then began travelling to 20 FSW. Ascent generally took 45-55 seconds.

(6) Fifteen minutes after the divers had started to purge their rigs, they stopped exercising and began a four minute rest period. This was followed by a six-minute work period and this 4/6 rest/work period alternation was carried out for the remainder of the 225 minute stay at 20 FSW.

(7) Oxygen fraction in the diver's UBAs was not controlled to 95%; the oxygen fraction in the UBA was whatever the purge procedure in Figure 3 produced.

(8) Spare UBAs were purged on the surface using the procedure in Figure 3.

(9) When changing UBAs, divers were directed to repurge only if their oxygen fraction fell to a level more than 5% below their initial oxygen fraction. Their initial oxygen fraction was considered to be that present in their UBAs after 10 minutes at 20 FSW at the start of the dive.

RESULTS

A total of 153 man-dives were either completed or resulted in toxicity episodes. Table 3 provides a summary of the dives accomplished and the toxicity episodes which occurred on each profile. The toxicity episodes were assigned to one of 3 categories: (A) Convulsion; (B) Definite; or (C) Probable. The toxicity episodes are described more fully in Table 4.

Toxicity Episode Classification

"Oxygen toxicity episode" refers to any combination of signs and symptoms occurring in a diver. Some episodes consisted of only one sign or symptom while other episodes consisted of several signs or symptoms. The "Convulsion" category requires no further elaboration except to say that all three convulsive episodes were of the classic grand mal, tonic-clonic type. "Definite" refers to episodes which were felt to have a high probability of resulting from oxygen toxicity. Episodes in which signs/symptoms such as muscle twitching, confusion, or aphasia occurred would generally result in a "Definite" classification. It should be emphasized, however, that other factors were also considered in determining the classification of a particular toxicity episode. Among these factors were the condition of the diver as noted by observers, the length of time the symptom persisted, and whether or not the dive was stopped at the time of the symptom. "Probable" episodes were those which were probably the result of CNS oxygen toxicity but which were more equivocal than those placed in the Definite category. Episodes consisting solely of such symptoms as nausea, dizziness, numbness, tingling, lightheadedness, or poor concentration generally resulted in the toxicity episode being classified as "Probable".

TABLE 3

PROFILE	Number of Man-Dives	Number of Subjects	TOXICITY EPISODES		
			CONVULSION	DEFINITE	PROBABLE
2-30	21	21	1	2	0
2-45	1*	1	0	1	0
2-60	42	36	1	2	2
3-90	11	11	1	2	2
40M-15	18	18**	0	1	2
40S-15(M)	30	25	0	1	2
40S-15	30	22**	0	1	0
TOTAL	153		3	10	8

NOTES:

* Three other divers were present on this dive but were stopped at the time of toxicity episode.

** The divers known to be oxygen-sensitive were not used on these profiles.

TABLE 4

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
2-30	001	30	CONVULSION	DYSPHORIA CONVULSION	60 Min	(1) Diver began to feel "a little weird" at about 50 minutes. (2) At the end of the profile, diver followed instructions to stop exercising and stand up, but did not stop oxygen breathing, did not respond to Tender and began moving in the wrong direction. Episode progressed to a convulsion.
2-30	005	41	DEFINITE	IRRITABILITY MUSCLE TWITCHING BLURRED VISION HYPOACUSIS	57 Min	(1) Diver reported being increasingly irritable throughout the latter part of the dive. Remembers being bothered by his mouthpiece and the movement of his breathing bag. (2) Muscle twitching began approximately one minute before diver stopped exercising. It started in the left foot, then spread to the other foot and increased in intensity. Also noted slightly blurred vision and hypoacusis.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
2-30	006	18	DEFINITE	MUSCLE TWITCHING	52 Min	(1) Approximately one minute prior to stopping, the diver thought that his foot was slipping out of the ergometer pedals. (2) Developed twitching of right and left hip extensors which increased in intensity until his Tender pulled him from his ergometer and took him off O_2. Also had twitching of his left arm.
2-45	007	48	DEFINITE	BLURRED VISION DIZZINESS AIR HUNGER APHASIA	75 Min	(1) Blurred vision began about two minutes before diver stopped. (2) Excursion was delayed 7 minutes because of an ear squeeze on descent. Toxicity episode occurred at 8 minutes into the excursion.
2-60	010	15	DEFINITE	MUSCLE TWITCHING DIZZINESS	78 Min	(1) Twitching of lips began about 2½ min before stopping. Spread to whole face and increased in intensity. Diver lost his mouthpiece seal and began offgassing; finally had to hold mouthpiece in with hand.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
2-60	015	42	DEFINITE	MUSCLE TWITCHING	15 Min	(1) Diver noticed that his legs were "going too fast" on the bicycle approximately two minutes before stopping. (2) Developed twitching of both legs.
2-60	017	6	CONVULSION	DYSPNEA CONVULSION	78 Min	(1) Diver was a female Diving Medical Officer. (2) Diver first noted difficulty breathing; occurred only several seconds before the onset of her convulsion. Diver felt that dyspnea may have been caused by spasms of her muscles of respiration. Came off ergometer on her own but became unconscious immediately after that.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
2-60	018	5	PROBABLE	HYPERACUSIS CIRCUMORAL PARESTHESIAS	87 Min	(1) At about 85 minutes into the dive, subject noted that there were intermittent brief periods during which sounds seemed louder than normal. (2) At about 87 minutes into the dive, subject noted that he felt "weird" and could not do anything but stare at his speedometer. Circumoral paresthesias then began. (3) Symptoms persisted until diver came off O_2. (4) Dive completed. Symptoms reported post dive.
2-60	019	37	PROBABLE	DIZZINESS TINNITUS	84 Min	(1) Approximately one minute before stopping, the diver became dizzy. Also noted a high-pitched sound in his ears.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
3-90	020	4	PROBABLE	DYSPHORIA CIRCUMORAL PARESTHESIAS	222 Min	(1) About 3 minutes before the end of the third excursion, the diver began to have a marked dysphoria, feeling that something was about to go wrong and that a severe toxicity episode was imminent. (2) Shortly after, he also began having circumoral paresthesias, characterized by marked tingling of the lips. (3) Symptoms increased in intensity until the end of the excursion, then slowly resolved after a return to 20 FSW. (4) Dive completed. Symptoms reported post dive.
3-90	021	15	CONVULSION	MUSCLE TWITCHING DYSPNEA DIZZINESS CONVULSION	63 Min	(1) One minute before convulsion, diver noted that his chest muscles were "vibrating" and that he was breathing in "spasms". Also felt dizzy. (2) Diver got off ergometer and spit out mouthpiece on his own but then went into convulsion.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
3-90	022	39	PROBABLE	NAUSEA CIRCUMORAL PARESTHESIAS	46 Min	(1) Diver was entirely well until about 8 minutes before he stopped. At that time he regurgitated some stomach contents into his mouthpiece and began to be nauseated with retching. (2) Nausea persisted some 15 minutes after diver discontinued oxygen breathing.
3-90	023	48	DEFINITE	BLURRED VISION DYSPNEA DIZZINESS CONFUSION	83 Min	(1) Approximately 5 minutes before stopping, diver began to notice blurred vision. (2) Diver was confused when he surfaced and had to be helped to the ladder.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
3-90	023	11	DEFINITE	NAUSEA TINNITUS ASPHASIA MUSCULAR RIGIDITY CONFUSION	95 Min	(1) Diver began to notice nausea about 10 minutes before stopping. (2) Ringing in ears began about 3 minutes before stopping, increased in intensity. (3) At 95 minutes, Tender noticed diver's arms going straight out from both sides and remaining rigid. Diver was still pedalling but did not respond to hand signals. Tender pulled him from his ergometer at that point. Diver was confused and aphasic after coming to the surface.
40M-15	026	26	PROBABLE	POOR CONCENTRATION AIR HUNGER TUNNEL VISION	132 Min	(1) Symptoms began 12 minutes into excursion. Went away upon return to 20 FSW. (2) Dive not stopped. Symptoms reported post-dive.
40M-15	026	36	PROBABLE	DIZZINESS LIGHTHEADEDNESS	137 Min	(1) Symptoms began just after excursion when diver was climbing ladder for a rig change. Lasted about 20 seconds. (2) Dive not stopped. Symptoms reported post-dive.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
40M-15	027	42	DEFINITE	WEAKNESS NUMBNESS MUSCLE TWITCHING	127 Min	(1) Diver noted that both legs began to feel "weak" about 4 minutes before stopping. (2) Just before stopping, the diver noted that both legs and his lower trunk (up to his chest) felt numb. He then began to have twitching of both legs and his left arm. (3) Neurological exam on surface was normal.
40S-15(M)	029	15	PROBABLE	DIZZINESS	115 Min	(1) Diver noted dizziness for about 45 seconds before stopping dive.
40S-15(M)	033	13	PROBABLE	BLURRED VISION NAUSEA RETCHING LIGHTHEADEDNESS	13 Min	(1) Diver noted slight blurred vision 2 minutes before stopping. Stopped after the nausea and retching began. (2) Was lightheaded briefly about 1 minute after discontinuing oxygen breathing.

TABLE 4
(Continued)

OXYGEN TOXICITY EPISODES
BY PROFILE

PROFILE	DIVE NUMBER	SUBJECT NUMBER	CLASS OF TOXICITY	SIGNS/SYMPTOMS NOTED (IN ORDER OF OCCURRENCE)	TIME REPORTED	COMMENTS
40S-15(M)	034	42	DEFINITE	PARESTHESIAS MUSCULAR RIGIDITY MUSCLE TWITCHING ASPHASIA	7 Min	(1) Diver noted sensation like a "low-voltage electrical shock" in both legs and lower trunk. Lasted about 10 seconds. (2) After 10 seconds, diver tried to get off ergometer but couldn't. Arms and legs would not respond. Tender saw diver's legs stop pedalling and left arm extend. (3) Tender took diver off of ergometer and noted that both legs were twitching. Diver was unable to respond to Tender's questions.
40S-15	038	46	DEFINITE	DIZZINESS SCOTOMATA LIGHTHEADEDNESS MUSCLE TWITCHING UNCONSCIOUSNESS	118 Min	(1) Diver noted dizziness and transient black spots in front of eyes about one minute prior to stopping. (2) Diver was preparing to notify his Tender that he felt "lightheaded" when he lost consciousness. (3) Tender noted both legs begin to twitch and removed diver from ergometer. Diver was essentially unconscious when brought to the surface but recovered quickly and did not suffer a convulsion.

The results of the dives by profile are shown in Figures 4 through 10. These figures show a graphic representation of the dive profile as well as the temporal location of any toxicity episodes noted on the profile. The profile and dive number noted for each episode also keys the reader to the more complete description of the toxicity episode contained in Table 4.

The first profile dove was Profile 2-30 as shown in Figure 4. Three toxicity episodes were noted in 21 man-dives, all of which were on the second excursion. This 14% incidence of serious toxicity episodes was felt to be too high and the transit time was lengthened to 45 minutes.

Another definite toxicity episode was noted on the first dive on Profile 2-45, as seen in Figure 5. At this point, it was decided to further lengthen the transit time in an attempt to completely eliminate any toxicity episodes on the second excursion. Only if the 60 minute transit (Profile 2-60) resulted in no definite hits or convulsions on the second excursion would Profile 2-45 be pursued further.

Forty-two man-dives on Profile 2-60 resulted in 1 convulsion and 2 definite oxygen toxicity episodes for a serious toxicity incidence of 7% (Figure 6). One definite episode occurred at the very end of the first 40 FSW excursion and did not reflect on the adequacy of the transit time. The other definite episode and the convulsion, however, took place during the second excursion and both occurred after only 3 minutes at 40 FSW which indicated that the transit interval was still inadequate. The transit time was again lengthened, this time to 90 minutes. A third excursion was also added; Profile 3-90 thus had 3 excursions to 40 FSW for 15 minutes, 90 minutes at 20 FSW between excursions, and a total dive time of 240 minutes.

Up to this point, the series had progressed as might be expected; an arbitrary initial transit time being lengthened based on the results of testing with a subsequent decrease in toxicity episodes on the second excursion. Profile 3-90, however, provided unexpected results (Figure 7). One convulsion and 2 definite hits were seen in 11 man-dives, an incidence of 27%. The most surprising aspect of the profile was that all 3 episodes occurred at 20 FSW. In neither of the previous two NEDU oxygen dive series[1,2] had any toxicity episodes categorized as convulsion or definite occurred at 20 FSW. Since the current U.S. Navy oxygen exposure limits shown in Figure 1 allow an initial excursion to 40 FSW for 15 minutes followed by 225 minutes at 20 FSW, two questions were raised by the results from Profile 3-90:

(1) Are the current U.S. Navy oxygen exposure limits safe?

and

(2) What was the reason for the serious toxicity episodes at 20 FSW where none had been observed previously?

At this point, the emphasis of the study was shifted to answer these two questions and investigations into the multiple excursions discontinued.

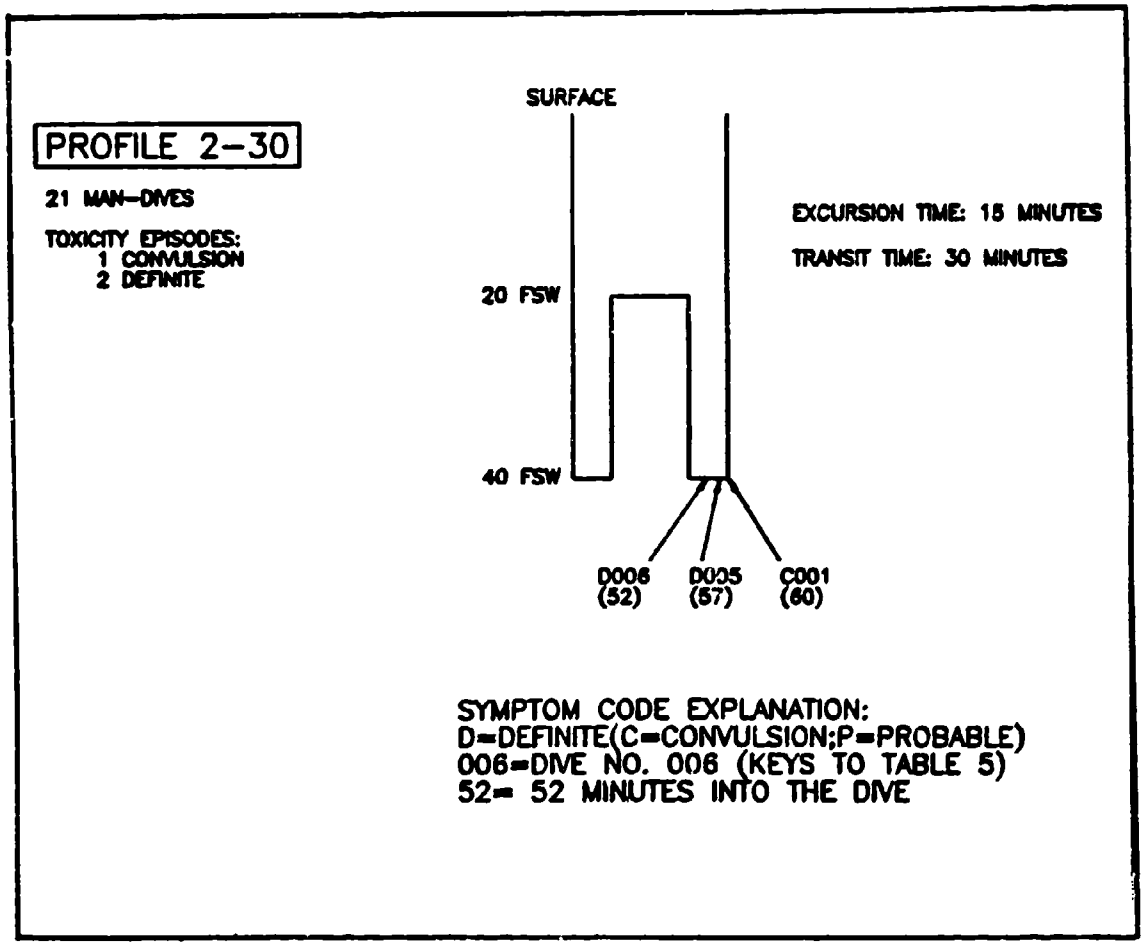
PROFILE 2-30
21 MAN-DIVES
TOXICITY EPISODES:
1 CONVULSION
2 DEFINITE
SURFACE
20 FSW
40 FSW
EXCURSION TIME: 15 MINUTES
TRANSIT TIME: 30 MINUTES
D006 (52)
D005 (57)
C001 (60)
SYMPTOM CODE EXPLANATION:
D=DEFINITE(C=CONVULSION;P=PROBABLE)
006=DIVE NO. 006 (KEYS TO TABLE 5)
52= 52 MINUTES INTO THE DIVE

FIGURE 4

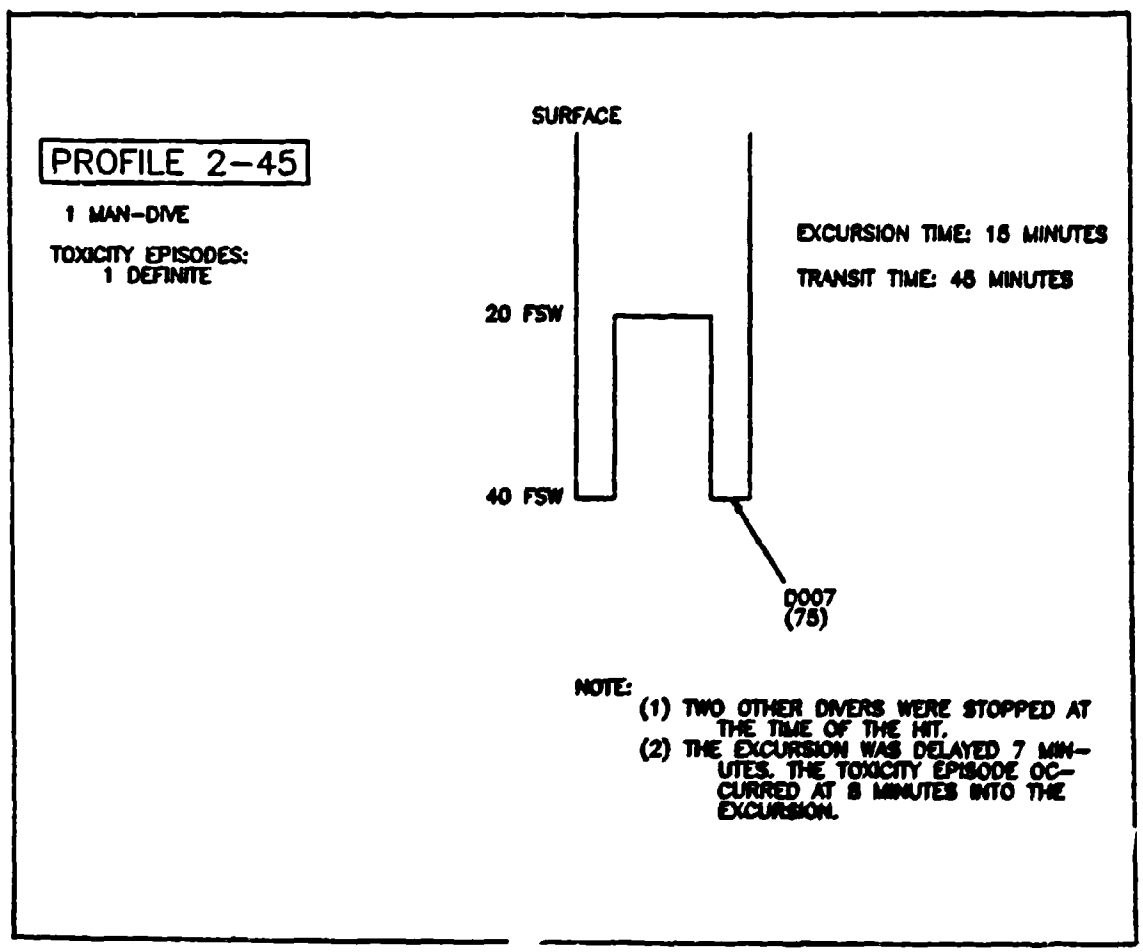
PROFILE 2-45
1 MAN-DIVE
TOXICITY EPISODES:
1 DEFINITE
SURFACE
20 FSW
40 FSW
0007
(75)
EXCURSION TIME: 15 MINUTES
TRANSIT TIME: 45 MINUTES
NOTE:
(1) TWO OTHER DIVERS WERE STOPPED AT THE TIME OF THE HIT.
(2) THE EXCURSION WAS DELAYED 7 MINUTES. THE TOXICITY EPISODE OCCURRED AT 8 MINUTES INTO THE EXCURSION.

FIGURE 5

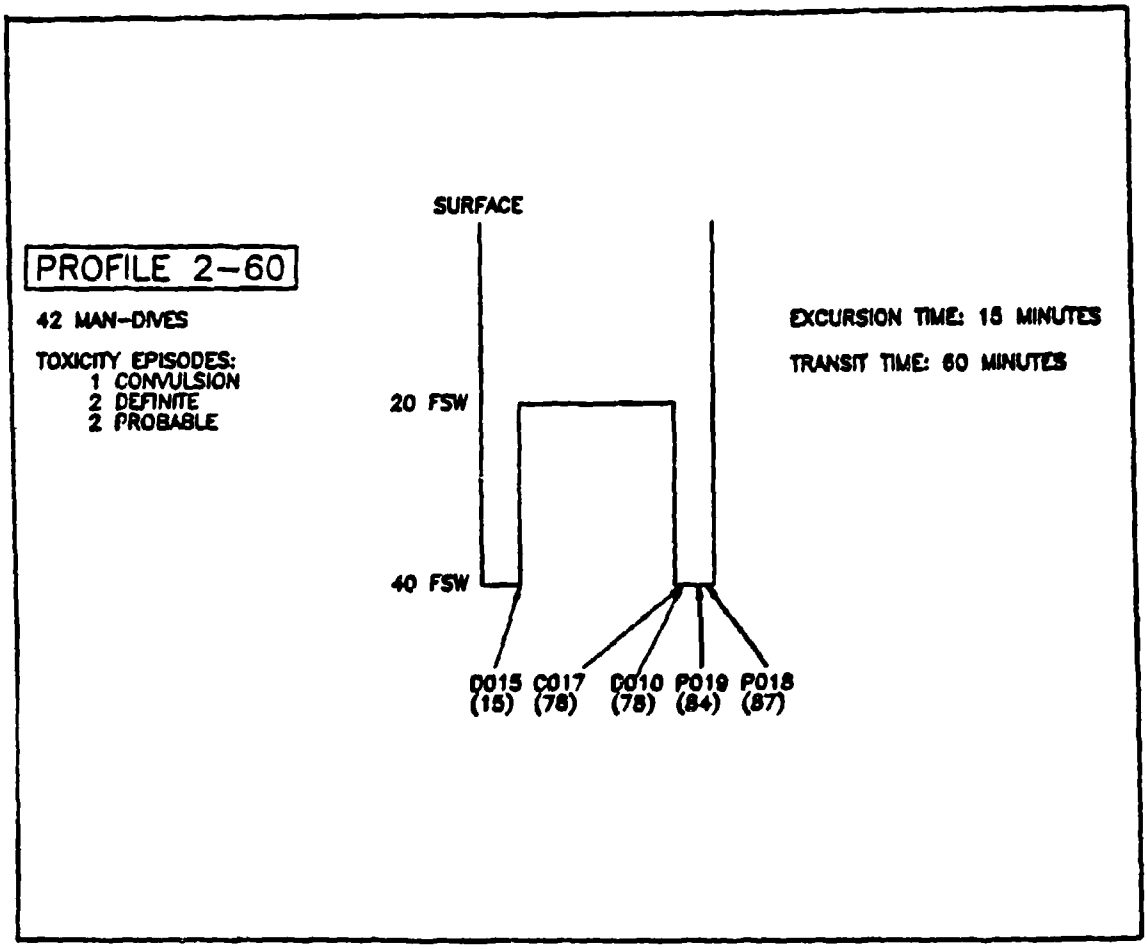
PROFILE 2-60
42 MAN-DIVES
TOXICITY EPISODES:
1 CONVULSION
2 DEFINITE
2 PROBABLE
SURFACE
20 FSW
40 FSW
EXCURSION TIME: 15 MINUTES
TRANSIT TIME: 60 MINUTES
D015 (15)
C017 (76)
D010 (78)
P019 (84)
P018 (87)

FIGURE 6

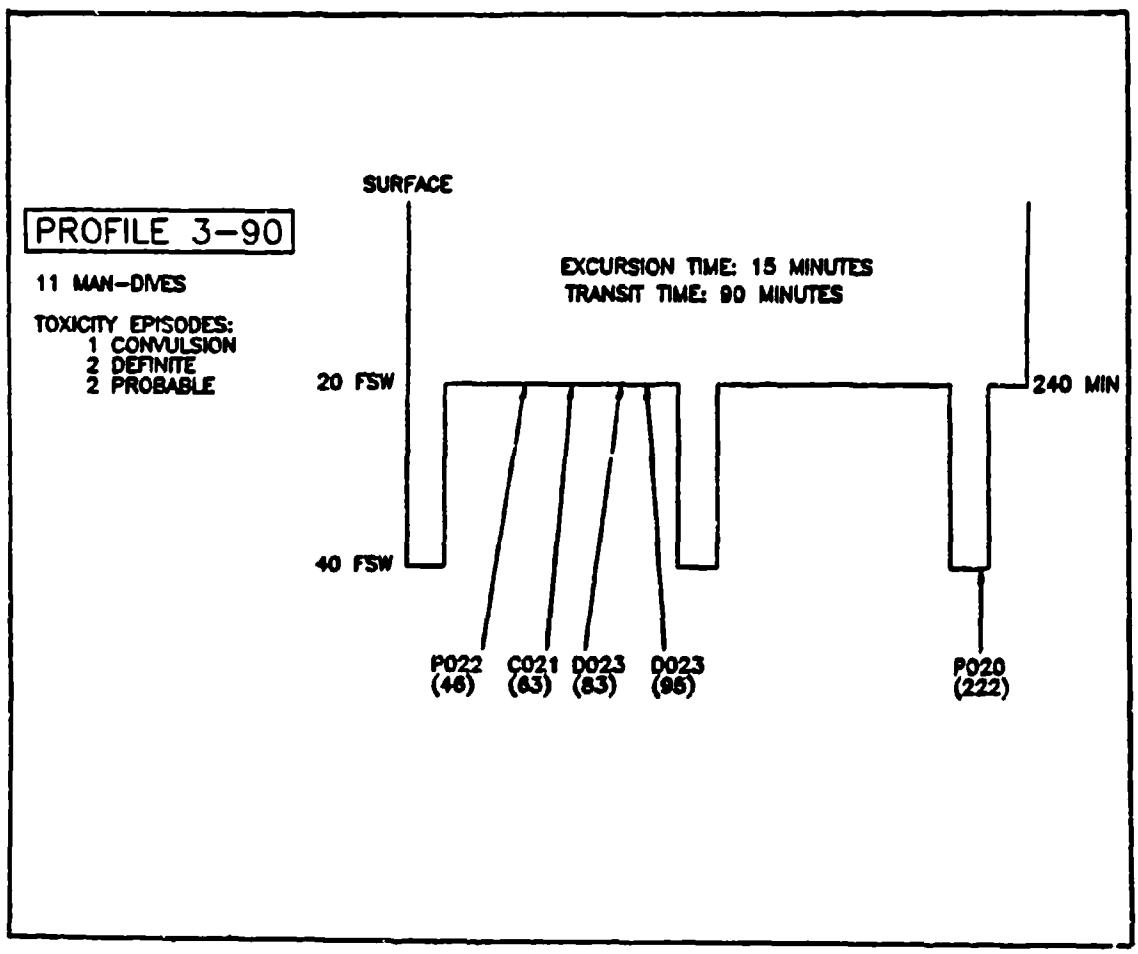
PROFILE 3-90
11 MAN-DIVES
TOXICITY EPISODES:
1 CONVULSION
2 DEFINITE
2 PROBABLE
SURFACE
EXCURSION TIME: 15 MINUTES
TRANSIT TIME: 90 MINUTES
20 FSW
40 FSW
240 MIN
P022 (46)
C021 (63)
D023 (83)
D023 (95)
P020 (222)

FIGURE 7

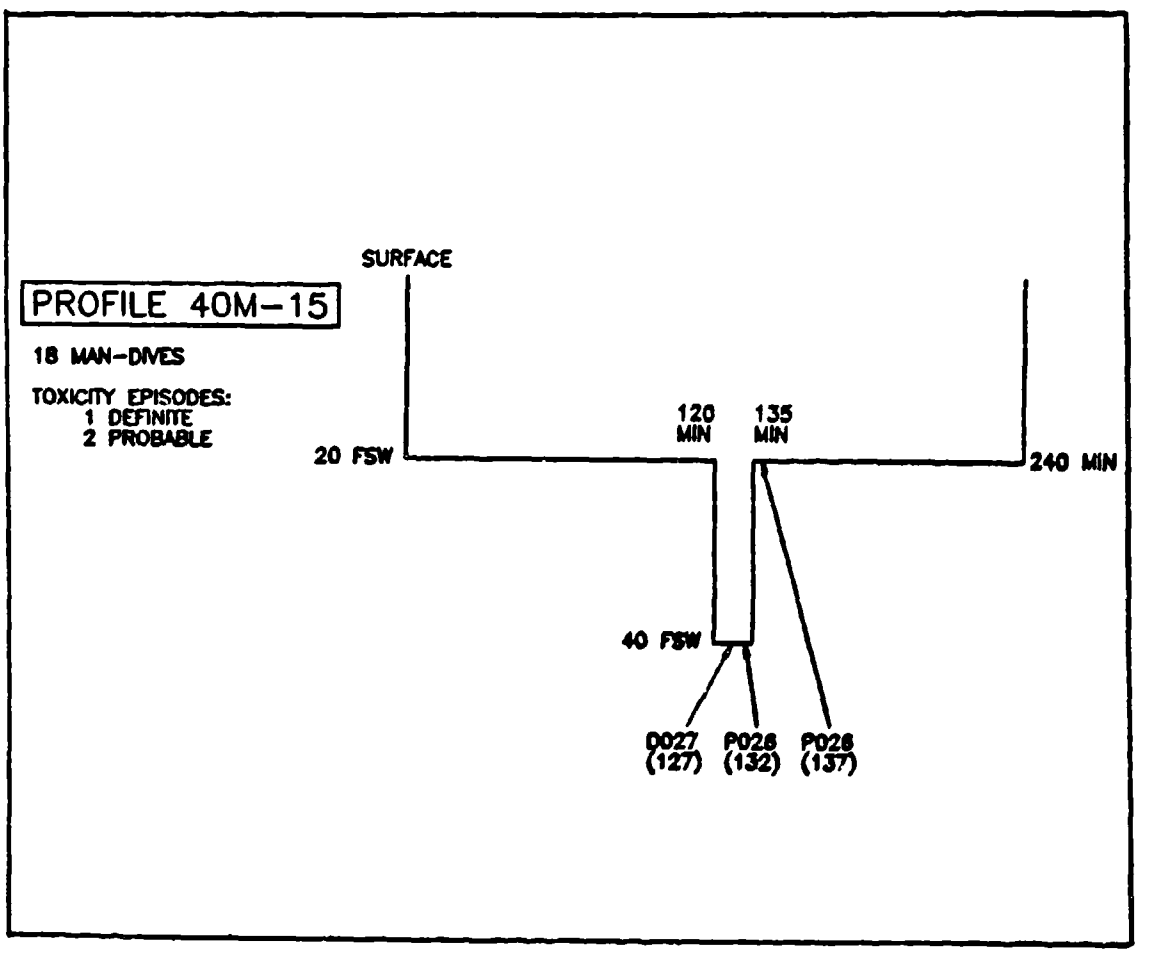
PROFILE 40M-15
18 MAN-DIVES
TOXICITY EPISODES:
1 DEFINITE
2 PROBABLE
SURFACE
20 FSW
120 MIN
135 MIN
240 MIN
40 FSW
D027 (127)
P028 (132)
P028 (137)

FIGURE 8

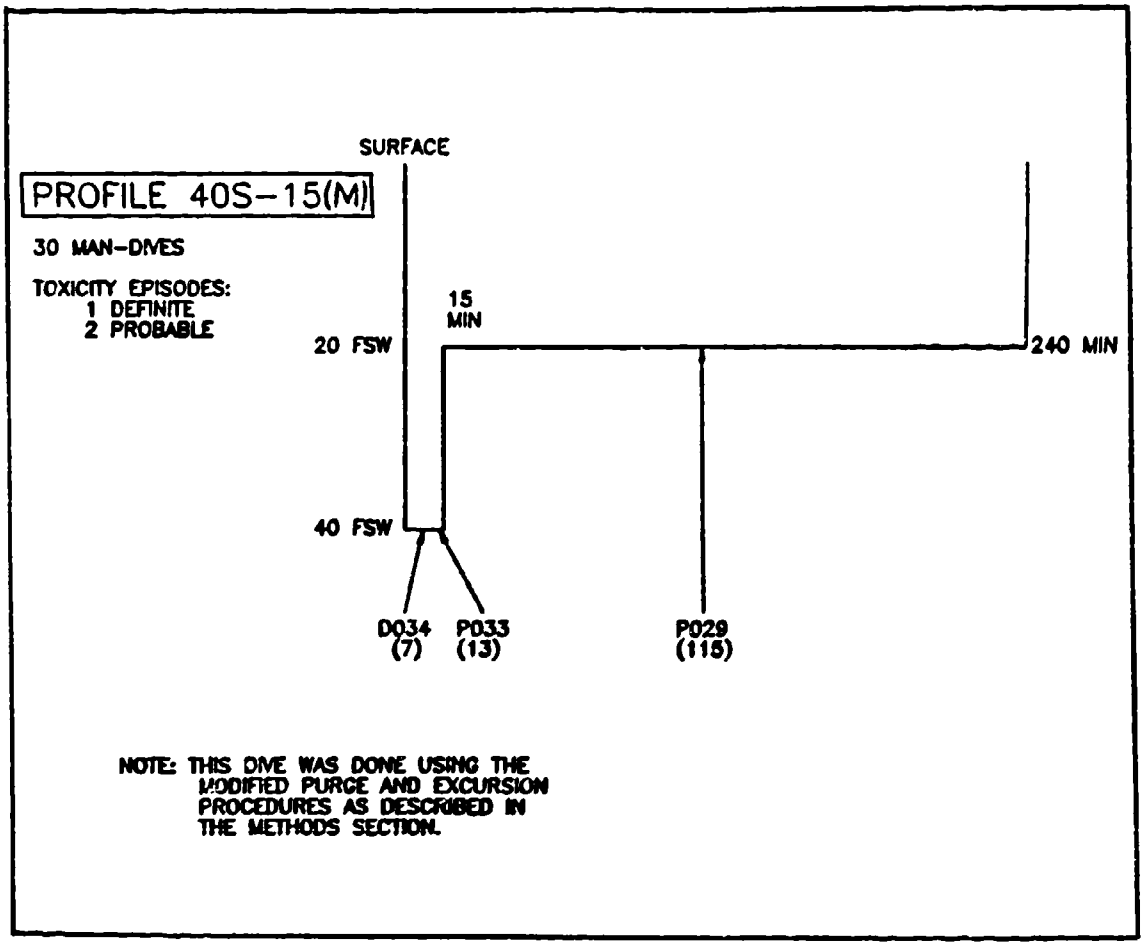
PROFILE 40S-15(M)
30 MAN-DIVES
TOXICITY EPISODES:
1 DEFINITE
2 PROBABLE
SURFACE
15 MIN
20 FSW
240 MIN
40 FSW
D034 (7)
P033 (13)
P029 (115)
NOTE: THIS DIVE WAS DONE USING THE MODIFIED PURGE AND EXCURSION PROCEDURES AS DESCRIBED IN THE METHODS SECTION.

FIGURE 9

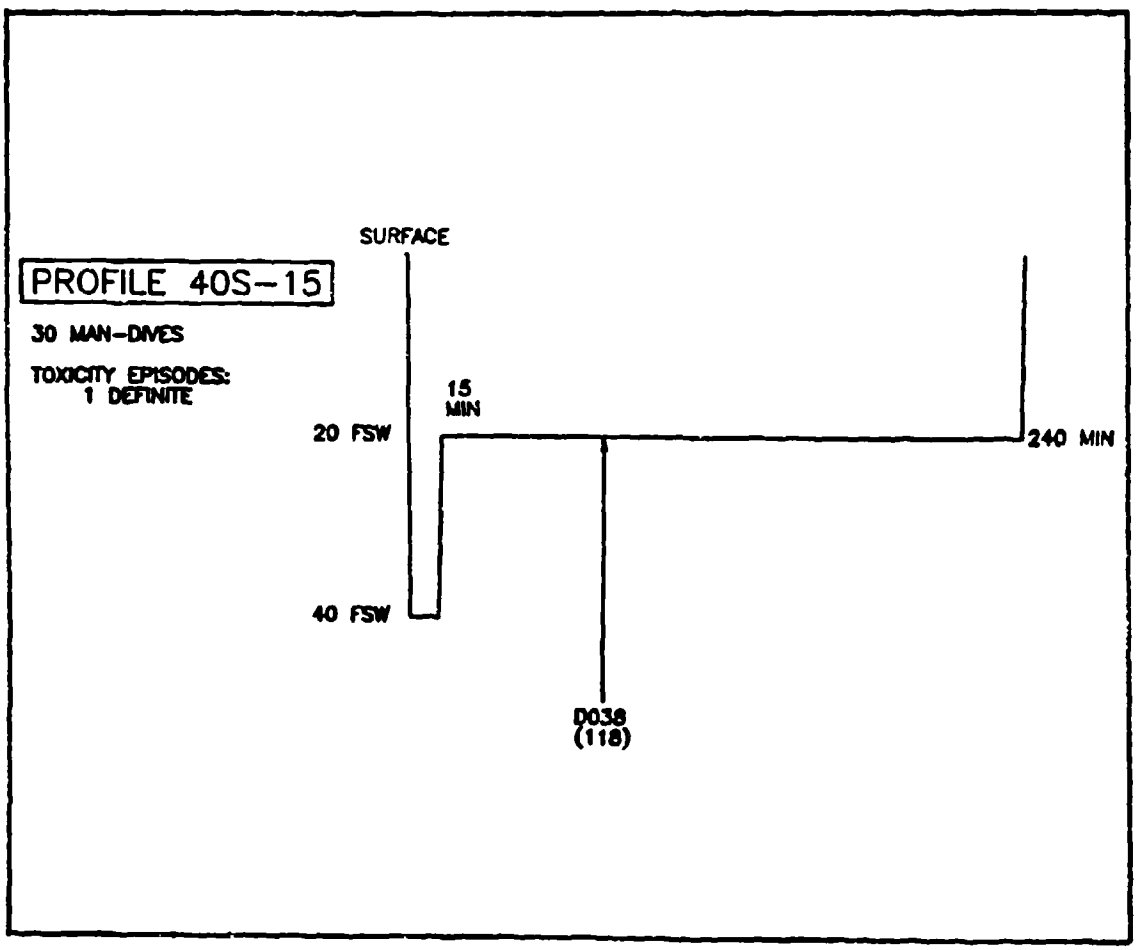
PROFILE 40S-15
30 MAN-DIVES
TOXICITY EPISODES:
1 DEFINITE
SURFACE
15
MIN
20 FSW
240 MIN
40 FSW
D038
(118)

FIGURE 10

The next profile dove was Profile 40M-15 (Figure 8). This profile was chosen because it had been dove 19 times in the 1983 series[2] with no episodes of oxygen toxicity. When dove in this series, it resulted in a single definite toxicity episode on the 40 FSW excursion. This result was not felt to be significantly different from the 1985 study. It is important to note that none of the three divers who had hits at 20 FSW on Profile 3-90 were dove on Profile 40M-15. The reason for this was that it was felt that all 3 divers might be unusually susceptible to oxygen toxicity. Had they been used on Profile 40M-15 and suffered additional toxicity episodes, they might have elected to withdraw from the study and not have the opportunity to dive Profile 40S-15(M). They were in effect, held in reserve, for this profile. One diver elected to withdraw at this point anyway.

Profile 40S-15(M) was designed to ascertain whether in fact the current oxygen exposure limits needed to be modified. For this profile, and this profile alone, the modified purge and excursion procedures described in the Methods section were used. These modifications were designed to eliminate several aspects of the experimental design which resulted in our initial excursions being a more severe oxygen exposure than an initial excursion using the current fleet procedures[4]. Profile 40S-15(M), therefore, was designed to more closely approximate the maximum oxygen stress a diver in the fleet would encounter if he were to make an initial excursion to 40 FSW followed by a 225 minute transit at 20 FSW. The modified purge procedure resulted in the mean UBA oxygen fraction being decreased from 97.2% for the rest of the series to 94.0% for this profile. In addition, the total time spent at the maximum depth of 40 FSW was reduced from approximately 18 minutes to 13 minutes by the changes in excursion procedures noted in the Methods section. As shown in Figure 9, Profile 40S-15(M) resulted in only 1 definite toxicity episode at 40 FSW in 30 man-dives. This episode occurred in the same individual who had had hits on the first excursion on Profile 2-60 and on the excursion in Profile 40M-15. There were no other definite hits or convulsions, despite the fact that two of the three divers who had had toxicity episodes on Profile 3-90 dove this profile.

Profile 40S-15 was then dove again; this time using the standard (more severe) experimental procedures. As seen in Figure 10, only a single toxicity episode was noted; that being a definite episode at 20 FSW, 118 minutes into the 4-hour profile. Note that on this profile the three divers who had had toxicity episodes classified as Definite or Convulsion at 20 FSW on Profile 3-90 as well as the diver who had the three toxicity episodes on the 40 FSW excursions were being subjected to special testing as described in the discussion section and did not dive on Profile 40S-15.

Table 5 provides a description of the relative frequency of occurrence of the various signs and symptoms of oxygen toxicity. Muscle twitching and dizziness were the most commonly noted events with 8 episodes each. Blurred vision was reported 4 times; dysphoria (used here to describe vague, generalized feelings of ill-being), convulsion, aphasia, dyspnea, paresthesias, and lightheadedness were all reported 3 times.

TABLE 5

SIGN/SYMPTOM	NUMBER OF TOXICITY EPISODES IN WHICH THE SYMPTOM WAS OBSERVED	% OF TOTAL SYMPTOMS (Rounded to Nearest Whole Percent)
MUSCLE TWITCHING	8	14
DIZZINESS	8	14
BLURRED VISION	4	7
DYSPHORIA	3	5
CONVULSION	3	5
APHASIAIA	3	5
DYSPNEA	3	5
PARESTHESIAS	3	5
NAUSEA	3	5
LIGHTHEADEDNESS	3	5
AIR HUNGER	2	3
TINNITUS	2	3
CONFUSION	2	3
MUSCULAR RIGIDITY	2	3
IRRITABILITY	1	2
HYPOACUSIS	1	2
HYPERACUSIS	1	2
POOR CONCENTRATION	1	2
TUNNEL VISION	1	2
GENERALIZED WEAKNESS	1	2
NUMBNESS	1	2
RETCHING	1	2
SCOTOMATA	1	2
UNCONSCIOUSNESS	1	2
TOTAL	59	

Core temperatures were monitored on the four hour dives. Sixty-six samples were taken in all with a mean core temperature drop rate of 0.20 ± 0.17°C/hr. For three divers suffering probable toxicity episodes, the core temperature drop rate was 0.09 ± 0.12°C/hr; while three divers with definite toxicity episodes had a mean drop rate of 0.41 ± 0.44°C/hr. Sixty divers without toxicity episodes had a mean core temperature drop rate of 0.20 ± 0.17°C/hr. The large standard deviations in core temperature drop rate in those individuals suffering oxygen toxicity symptoms do not allow any conclusion to be made regarding the effects of thermal stress on oxygen toxicity.

Although baseline pulmonary function studies were done, there was no plan to monitor pulmonary function during the dive series unless actual symptoms developed since previous studies[2] had produced no symptoms of pulmonary oxygen toxicity in similar oxygen exposures of up to 265 minutes. A number of divers in this series, however, had mild symptoms of substernal discomfort and cough felt to be compatible with early pulmonary oxygen toxicity. Pulmonary function tests (Forced Vital Capacity) were subsequently done on all divers who completed the first of the two daily four-hour dives. Forty-three divers were tested. Of these, 19 complained of sight symptoms of cough or substernal chest discomfort. Studies revealed an insignificant decrease in FVC of 1.72 ± 2.99%. All symptoms were relatively minor and resolved completely within 24 hours.

DISCUSSION

SYMPTOM WEIGHTING AND ESTABLISHING LIMITS

One of the major difficulties in evaluating the safety of a proposed exposure limit for oxygen diving lies in determining the relative importance of various toxicity episodes. The NEDU classification of toxicity episodes as convulsion, definite and probable is described in the Methods section and is consistent with our two previous studies[1,2]. Also outlined in the second reference cited is a discussion for the rationale used to determine how the results of our experimental dives should be applied to developing a set of operational oxygen exposure limits. To summarize;

(1) Dive profiles were shortened only on the basis of definite toxicity episodes or convulsions;

(2) Multiple episodes of definite hits or convulsions noted at or beyond a certain point in time on a particular dive profile resulted in the profile being modified (shortened).

(3) Profiles were generally not modified as a result of a single toxicity episode, no matter what the classification.

MULTIPLE EXCURSION TESTING

Similar criteria were applied to evaluating the multiple excursion profiles in Figures 4-10. Profile 2-30 had an unacceptably high incidence of serious toxicity episodes (definite episodes or convulsions) on the second excursion. Extension of the transit interval at 20 FSW by 15 minutes (Profile 2-45) resulted in a definite toxicity episode on the first dive attempted. Profile 2-60 was more successful, causing only 2 definite hits and 1 convulsion in 42 man-dives. One of the definite episodes occurred at the end of the initial excursion and was therefore not useful in judging the adequacy of the recovery time between excursions. This toxicity episode was in fact the first definite toxicity episode or convulsion noted in 145 trials of 40 FSW for 15 minutes oxygen exposures as a square dive or as an initial excursion up to that point in time (81 from previous dive series[1,2], 64 in this series). The diver who suffered this toxicity episode went on to have a second similar episode on an initial excursion as described later. The two serious toxicity episodes in 41 trials of the second excursion after a transit interval of 60 minutes was a much lower incidence than noted with a 30 minute transit interval at 20 FSW (5% vs 14%); the transit time was extended to 90 minutes in Profile 3-90 to see if this would further decrease the toxicity episodes on the second excursion.

Profile 3-90 did not, in fact, have any definite toxicity episodes or convulsions occur on any of the excursions, but only 11 man-dives were done on this profile because of the unexpected occurrence of three serious toxicity episodes at 20 FSW between the first and second excursions.

The improvement in toxicity episodes on subsequent excursions was overshadowed by the high incidence of toxicity episodes at 20 FSW. Definite toxicity episodes or convulsions using closed-circuit oxygen at 20 FSW have never been previously reported, possibly because earlier researchers felt that exposures at these shallow depths were safe and did not require extensive testing. While studying the transit with excursion concept, the dive series at NEDU in 1983[2] conducted 153 exposures of four hours at 20 FSW with one or two downward excursions. No definite toxicity episodes or convulsions were noted in any of these dives, except during or immediately (within 5 minutes) after the excursions. When the toxicity episodes at 20 FSW in this dive series occurred, the emphasis of the research was shifted to determine whether or not the 1984 oxygen exposure limits shown in Figure 1 should be made more restrictive and to investigate the reason for the serious toxicity episodes at 20 FSW where none had been observed previously.

The 1984 oxygen exposure limits were approved for Fleet use in July of 1984[10] and subsequently incorporated into the recently revised U.S. Navy oxygen diving procedures[4]. At the time of this report, there have been no incidents of oxygen toxicity reported using the new limits, even though there is a greater potential for CO_2 buildup, poor depth control, and excessive

exercise rate in the field as opposed to the experimental setting. Despite this excellent safety record to date, these procedures, which allow a single excursion to 40 FSW for 15 minutes to be taken at any time during the dive, would seem to place the diver at significant hazard if the excursion is taken at the beginning of the dive in light of the results noted on Profile 3-90.

In beginning to address the question of the safety of these limits, an introductory word about the design of an experimental study to investigate physiological limits in diving is in order. There are myriad possible combinations and permutations of environmental and diver variables which may exist for any given dive. It is manifestly impossible to test each set of conditions, so a number of assumptions must be made. In some cases, a "worst case" condition is assumed; in others, a reasonable estimate of the variable in question is made. For example, immersion[11] and work[11,12,13] have both been shown to potentiate the toxicity of hyperbaric oxygen. In the case of the former, having the divers in the water represents a worst case scenario, and one may say with confidence that oxygen exposure limits which are safe for immersed divers may be expected to be even more so for dry divers. On the other hand, "work" covers a spectrum of activity ranging from intermittent, minimal activity to maximum oxygen consumption. It is obviously impossible to establish a safe oxygen exposure limit for a 4 hour dive at maximum oxygen consumption because no diver can sustain that level of exercise for 4 hours. In this case a reasonable figure for diver oxygen consumption while swimming was determined and the test accomplished to this criteria. Establishment of a test plan with conditions that will yield results that are conservative, but not unreasonably so, is a delicate balance.

As a result of previous testing[2], among the assumptions made were that: (a) An excursion which is safe for a given period of time will be safe for any shorter period of time; (b) the excursions were the portions of the dive (on transit with excursion profiles) which entailed the greatest risk of oxygen toxicity; and (c) if a single excursion could be made safely at a given point in the dive, it could also be made safely at any point prior to that in the dive profile. In that series[2], the diver's oxygen was maintained at a level of 95% or greater. The excursions were designed such that the diver spent <u>all</u> of the designated excursion time at the maximum depth of the excursion. Travel to and from the excursion depth was counted as part of the transit time. Initial excursions were not done in the previous two NEDU series.

For this series, an initial excursion was included. In order to ensure that the entire excursion time was spent at the excursion depth, the divers were compressed to 40 FSW on air and began their excursion time only after completing their UBA purge procedure. The actual time spent at 40 FSW was several minutes longer than the 15 minutes shown. The purge time was 1½ to 2 minutes and travel time from 40 FSW to 20 FSW was approximately 40 seconds. The divers were therefore exposed to oxygen at a depth greater than 20 FSW for roughly 18 minutes before arriving at the transit depth.

Since the new oxygen-diving procedures outlined in NEDU Report 7-85 call for oxygen breathing at all depths deeper than 20 FSW to be counted as excursion time and also would count the extra 1¼ - 2 minutes purging at 40 FSW as excursion time, a modified excursion procedure was devised for Profile 40S-15 (M). This profile was designed to provide a much closer approximation of the maximum oxygen toxicity stress of the profile as it would be dove in the Fleet. Note that the excursion is still performed at the beginning of the dive. Also important to note is that all but one of the divers who had experienced toxicity episodes on Profile 3-90 dove Profile 40S-15 (M); the single diver who did not dive this profile had suffered two definite toxicity episodes by this point and elected to withdraw from the study. The other major change in Profile 40S-15 (Modified) was that the purge procedure was changed; rather than require a minimum O_2 percentage of 95%, the divers performed the standard purge used in the Fleet[3,4]. The modified conditions of 40S-15 (Modified) resulted in an average UBA oxygen level of 94.0% and a time at 40 FSW of approximately 13 minutes as opposed to the average of 97.2% oxygen and 18 minutes at 40 FSW observed with the first excursion on Profile 3-90. The only definite toxicity episode on this profile occurred in the same individual who had a toxicity episode on the first excursion of Profile 2-50 and on the single excursion in Profile M-15. This diver was felt to be unusually oxygen susceptible on the basis of these multiple toxicity episodes and will be discussed later along with the two other oxygen-susceptible individuals who were identified in the course of the series. The single definite episode on Profile 40S-15 (M) is considered to indicate an acceptable level of risk for the currently used oxygen exposure limits although the occurrence of this single toxicity episode underscores the fact that it is impossible to completely eliminate the hazard of oxygen toxicity when diving with closed-circuit oxygen SCUBA.

The presence of oxygen susceptible individuals such as the diver who suffered the definite toxicity episode on Profile 40S-15 (M) and the high incidence of toxicity episodes noted on Profile 3-90 make incorporation of multiple excursion options into the oxygen exposure limits ill-advised at this time. Multiple excursion options as well as greater depths and/or exposure times may be possible in the future for closed-circuit oxygen diving through use of such measures as improved screening procedures to detect relatively oxygen-sensitive individuals, incorporation of a device into the closed-circuit oxygen UBA which would introduce a measured amount of nitrogen into the UBA if an emergency downward excursion is required, or pharmacologic protection from oxygen toxicity.

TOXICITY EPISODES AT 20 FSW

The second major question to be addressed in the latter part of the dive series was the reason for the unexpectedly high incidence of toxicity episodes at 20 FSW in Profile 3-90. The first possibility considered was that perhaps there had been some inadvertent change in the test conditions. A careful review of the experimental procedures looking at such factors as diver population, thermal conditions, and work rate did not reveal any such change.

An important observation with respect to this possibility is obtained by comparing the initial 40 FSW excursions as well as the 20 FSW exposures in this dive series with those on the previous dive series. Any systematic change increasing the stressfulness of the oxygen exposures should be reflected in an increase in toxicity episodes at 40 FSW as well as at 20 FSW, although a similar pattern might be obtained if the diver population contained a proportionately larger number of oxygen susceptible individuals. Tables 5 and 6 contrast the results of both the 40 and 20 FSW exposures in this and the previous NEDU dive series[1,2].

The 40 FSW initial exposures saw 1 definite hit in 107 dives as compared to none in 81 dives on the previous series. The individual who encountered this toxicity episode also had a definite toxicity episode at 40 FSW on Profile 40S-15 (M), despite the reduced oxygen stress on that exposure. Thus, in 188 total exposures, he is the only diver to develop signs of oxygen toxicity on this profile. The results of the 40 FSW exposures in this study, therefore, were felt to be remarkably consistent with those from the 1983 study.

A marked increase in toxicity was noted for the 20 FSW exposures, however, with 3 definite episodes and 1 convulsion in 56 dives being noted in this series as compared to none in 153 dives previously. Of these four episodes, two were noted in individuals identified as being oxygen susceptible while the other two episodes occurred in divers who had no other toxicity episodes during the study. Comparing the 20 FSW and the 40 FSW exposures clearly does not support the proposition that the overall experimental conditions were more stressful in some unknown way.

A second possible explanation for the toxicity episodes at 20 FSW is that this study contained a number of unusually oxygen-susceptible individuals. Marked variation between individuals with respect to oxygen tolerance was noted by Donald[11] and confirmed in subsequent studies[1,2]. The relatively large sample size (48 divers) used in this study was prompted by a desire to ensure that a wide range of individuals be exposed to the experimental profiles. Examination of Table 4 reveals that 3 divers (#42, #15, and #48) experienced multiple episodes of oxygen toxicity in the definite or convulsion category. Diver #42 made 4 dives and had 3 definite toxicity episodes, all of which occurred during the 40 FSW excursions. In addition to being the only individual ever to have had a toxicity episode on a 40 foot for 15 minute exposure without a pre-exposure, as noted above, he also had a definite toxicity episode at 40 FSW on Profile 40M-15, which was the only definite episode of 37 man-dives on this profile (considering both the current and 1983 series). Diver #15 also had 3 toxicity episodes in 4 dives, including the only oxygen convulsion ever recorded at 20 FSW. Diver #48 had 2 definite episodes in 2 dives and decided to withdraw from the study. Of the three, two were from the SEAL teams and the other was an NEDU saturation diver. Since the diver-subjects were drawn approximately equally from both groups (22 NEDU, 26 SEAL), there is no evidence to support the theory that the oxygen susceptible individuals tended to be primarily those who were not experienced combat swimmers.

TABLE 5

40 FSW EXPOSURES

Dive Series	Profile	40 FSW For 15 Minute Exposures (No Pre-exposure)	TOXICITY EPISODES Convulsion	Definite	Probable
1982	(40 ft/20 min)	17	0	0	1
	(40 ft/15 min)	24	0	0	5
1983	40-15	40	0	0	1
TOTAL		81	0	0	7
1985	2-30	21	0	0	0
	2-45	3*	0	0	0
	2-60	42	0	1	0
	3-90	11	0	0	0
	40S-15(M)	**	**	**	**
	40S-15	30	0	0	0
TOTAL		107	0	1	0

NOTES:

* The additional two divers shown here who are not shown in Table 3 represent two divers who made the initial excursion but were stopped at the time of the toxicity episode and did not complete the profile.

** The results of 40S-15 (M) are not included because the different test conditions established for this profile decreased the oxygen toxicity stress of the exposure as compared to all the other dives shown in the table.

TABLE 6

20 FSW EXPOSURES

Series	Dive Profile	20 FSW For 4 Hr Exposure	TOXICITY EPISODES Convulsion	Definite	Probable
1983	See Ref 2	153*	0	0	12
	TOTAL	153*	0	0	12
1985	3-90	11	1	2	1
	4)-15(M)	**	**	**	**
	40S-15	30	0	1	0
	40M-15	15	0	0	0
	———	—	—	—	—
TOTAL		56	1	3	1

NOTES:

* Profiles counted here include all profiles to 4 hours. All profiles had downward excursions during the dive. Divers who had toxicity episodes during the excursion or within 5 minutes of the excursion are not included in the totals.

** The results of 40S-15 (M) are not included because the different test conditions established for this profile decreased the oxygen toxicity stress of this exposure as compared to the other dives shown in the table.

These 3 divers were each subsequently administered a total of 4 U.S. Navy standard Oxygen Tolerance Tests (OTT) consisting of 30 minutes of breathing oxygen at 2.8 ATA (60 FSW) in a dry chamber. Table 7 shows the dives made by these susceptible divers, the toxicity episodes encountered, and the results of the oxygen tolerance testing. Although these divers experienced 8 toxicity episodes out of a total of 10 experimental exposures, the 12 OTT's administered to these divers produced only 1 episode of equivocal symptoms. This is in agreement with previous findings[1,2] that the Navy Oxygen Tolerance Test, although it does have a 1-2% failure rate, is not sensitive enough to identify the divers who have suffered repeated episodes of oxygen toxicity during the 3 NEDU oxygen dive series on profiles that the vast majority of the other test subjects were able to tolerate without difficulty. The implications of this finding are discussed elsewhere[14]. The presence of these three relatively oxygen-susceptible divers certainly accounts in part for the toxicity episodes noted at 20 FSW (2 of the 4 episodes at 20 FSW were seen in these 3 divers).

A third possibility is that performing the 40 FSW excursion at the beginning of the four hour exposure in some way renders the diver more susceptible to oxygen toxicity during the subsequent transit period at 20 FSW. This phenomenon was not observed in the 1983 NEDU dives when the excursions to 35, 40, and 50 FSW were performed in the middle of the dive profiles. Although the 35 and 50 FSW excursions are not directly comparable to the 40 FSW excursions, their toxicity stress seems to be equal to or greater than the 40 FSW excursion in that the times of 25 and 10 minutes, respectively, used in the previous study for these depths had to be subsequently reduced when the 1984 limits were recommended whereas the 40 FSW time of 15 minutes was not changed. Table 8 shows an analysis of the toxicity episodes noted at 20 FSW between the excursion in the middle of the profile and the end of the 4 hour period in the 1983 dive series. As noted in Table 8, out of 86 exposures at 20 FSW for 95-110 minutes (depending on the duration of the first excursion), no definite toxicity episodes or convulsions were noted and only 2 probable hits were seen. Why would an excursion at the very start of the dive be more likely to result in a subsequent toxicity episode at 20 FSW than an excursion at the middle of the profile? The cumulative oxygen dose was much less prior to the toxicity episodes at 20 FSW noted in this series than in those following an excursion in the middle of the dive in the previous series.

A review of the literature was not helpful; no previous reports of experimental multi-level oxygen diving studies in man were noted. One is tempted to suggest that the 20 FSW exposure prior to an excursion might allow induction of protective physiologic mechanisms. This phenomenon has in fact been reported in previous animal models examining the effects of prior hyperoxic exposures on the development of pulmonary oxygen toxicity; in some species, the development of pulmonary oxygen toxicity was delayed by previous intermittent exposure to a hyperoxic atmosphere.

TABLE 7

OXYGEN-SUSCEPTIBLE DIVERS

TOXICITY EPISODES

Diver Number	Total Dives	Convulsion	Definite	Probable	Oxygen Tolerance Tests	Toxicity On Oxygen Tolerance Tests
15	4	1	1	1	4	0
42	4	0	3	0	4	0*
48	2	0	2	0	4	0

* This diver developed symptoms of paresthesias of legs, hands, and feet after four minutes of breathing oxygen at 60 FSW. Subsequent questioning revealed that he had had symptoms of leg fatigue and numbness following an air dive as a tender several days earlier which had not been reported. He was then treated for Type II Decompression Sickness with complete relief after three Table Sixes. The symptoms noted on the oxygen tolerance test probably represented the onset of the therapeutic effect of hyperbaric oxygen on the pre-existing decompression sickness, rather than oxygen toxicity.

TABLE 8

TOXICITY EPISODES AT 20 FSW
AFTER AN EXCURSION IN THE MIDDLE OF THE PROFILE
(1983 NEDU Dive Series)

PROFILE	EXPOSURES	CONVULSIONS	DEFINITE	PROBABLE
35M-25	18	0	0	0
35EM-25	14	0	0	0
40M-15	19	0	0	0
50M-10	16	0	0	0
50EM-10	19	0	0	2
TOTAL	86	0	0	2

intermittent exposure to a hyperoxic atmosphere. This change was associated with elevation in the levels of several enzymes known to have a protective anti-oxidant function[15,16,17]. Whether or not such an induction occurs in a single exposure has not been established. Certainly no long-term accommodation to oxygen stress was noted in the three oxygen-susceptible divers in this series. The only two toxicity-free dives made by these divers both occurred on the first exposure for the respective divers; additionally, these two exposures were on the profile (2-30) which produced the highest incidence of toxicity episodes overall. No protective influence from the preceding 20 FSW exposures was noted on the excursions in the 1983 series[2]; rather, one of the conclusions from this series was that "20 FSW pre-exposures for 2 and 4 hours seem to slightly increase the probability of an oxygen toxicity episode on subsequent excursions but there is not a consistent difference between the effects of the pre-exposure lengths". This disparity poses several questions which cannot be answered from this study: (1) Are pulmonary and CNS oxygen toxicity the result of the same pathological process?; (2) Why did the toxicity episodes at 20 FSW occur so far removed in time from the excursion?; (3) Why were no toxicity episodes noted at 20 FSW in the previous dive series (or this one) after an excursion in the middle of the four-hour dive?; (4) What is the significance of the temporal proximity of the 20 FSW toxicity episodes (all 4 episodes occurred in the interval from 63 to 118 minutes in a 240 minute profile).

PULMONARY OXYGEN TOXICITY

The presence of early symptoms of pulmonary oxygen toxicity noted in this study indicates that pulmonary toxicity may in fact be a limiting factor in closed-circuit oxygen diving operations. Although both the minor nature of the symptoms noted and the minimal changes in Forced Vital Capacity represent only the earliest stage of pulmonary oxygen toxicity, the additional possibility of a diving accident must be considered. Should an oxygen diver experience a gas embolism, which is much more likely on closed as opposed to open-circuit SCUBA, he may require an oxygen Treatment Table 6A. Using the Unit Pulmonary Toxic Dose methodology described by Wright[18] and based on the pioneering work of Clark and Lambertsen[19,20], the UPTD for a four hour dive at 20 FSW would be 463. Profile 40S-15 would result in a dose of 476 UPTD. Although this is somewhat less than the 615 UPTD cited as producing a 2% drop in FVC and the earliest symptoms of pulmonary oxygen toxicity, the 615 figure was based on resting subjects in a dry chamber. The known potentiating factors of immersion and exercise may explain these changes occurring at an earlier time. A change of this magnitude would still allow a diver to complete a Treatment Table 6A and be within the limits recommended by Wright[18] for a maximum therapeutic oxygen dose. Additional evidence in favor of considering a maximum daily oxygen exposure is found in another study[21] which reported symptoms of fatigue, headache, dizziness, paresthesias and pulmonary symptoms suspected to be caused by chronic oxygen toxicity in two groups of divers exposed to doses of 600 and 800 UPTD per day over several weeks. Based on these considerations, an oxygen time of four hours per day is recommended as a maximum figure for closed-circuit oxygen diving. Although multiple dives to a deeper depth might result in a larger total UPTD per day than that noted for 20 FSW dives, the two-hour interval required between repeated oxygen dives would allow a measure of recovery.

SYMPTOMS OF CNS OXYGEN TOXICITY

The symptoms of CNS O_2 toxicity encountered on this series as presented in Table 4 display considerable variation from previous dive series[1,2]. The first NEDU dive series recorded a preponderance of lightheadedness, dysphoria, and apprehension. The second study saw nausea reported most frequently despite the fact that it had not been reported a single time in the first series. The present study resulted in dizziness and muscle twitching being observed most frequently. These marked differences from series to series may result from a suggestibility factor present in the diver subjects. If several divers on the previous day had reported nausea, a diver might be very alert for any trace of this symptom and relatively quick to report it. These differences emphasize the equivocal nature of the "probable" symptom category, in light of the fact that more objective symptoms such as muscle twitching and convulsion have been noted consistently throughout.

THERMAL EFFECTS

The correlation between core temperature drop rate and toxicity episodes noted in the previous study[2] was not seen in this study. The relatively small number of toxicity episodes on which core temperature was monitored and the large standard deviations in the rate of core temperature drop prevent statistical significance from being achieved. Additionally, separate analysis of the probable toxicity episodes as opposed to the definite episodes and convulsions reveals that the two categories are opposite in direction from the mean of those divers without toxicity episodes; the probable episodes had a slower rate of core temperature drop while the definite episodes noted had a more rapid drop.

CONCLUSIONS

(1) Increasing the time at 20 FSW between downward excursions from 30 minutes to 60 minutes reduced the incidence of serious toxicity episodes from 14% to 5%. A 90 minute transit time eliminated toxicity episodes on subsequent excursions, but the number of dives on this profile was small.

(2) An initial excursion to 40 FSW for 15 minutes rendered divers susceptible to subsequent oxygen toxicity at 20 FSW. This effect is lessened, but not eliminated, by discounting the toxicity episodes at 20 FSW encountered by the oxygen sensitive divers in the study.

(3) No multiple excursion options are recommended at this time, but the 1984 oxygen exposure limits should continue to be used as previously published.

(4) The U.S. Navy standard Oxygen Tolerance Test was not sensitive enough to produce symptoms in the three oxygen-susceptible divers identified in this dive series. Extensions of the current limits and multiple downward excursions will probably not be feasible until a more sensitive method of identifying oxygen sensitive individuals is found.

(5) Minor symptoms of pulmonary oxygen toxicity were noted after some of the four hour dives. A maximum of four hours oxygen time per twenty-four period is recommended for closed-circuit oxygen diving operations.

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APPENDIX 1

CHRONOLOGIC RECORD OF PROFILES ACCOMPLISHED BY DIVERS

DIVER NO.	NOVEMBER 1985								DECEMBER 1985											
	11-14	11-15	11-18	11-19	11-20	11-25	11-26	11-27	12-2	12-3	12-04	12-5	12-6	12-9	12-10	12-11	12-12	12-13	12-16	12-17
1				2-30*			2-60										40S-15			
2			2-30		2-60															
3							2-60*													
4			2-30		2-60			3-90 (P)												
5							2-60 (P)													
6							2-60 (C)													
7			2-30		2-60				3-90											
8							2-60													
9				2-30													40S-15			
10						2-60														
11	purge								3-90 (D)				40S-15(M)				OTT	OTT	OTT	OTT
12																	40S-15			
13				2-30*			2-60								40S-15(M) (P)					
14			2-30		2-60							40M-15								
15		purge	2-30		2-60 (D)			3-90 (C)					40S-15(M) (P)				OTT	OTT	OTT	OTT
16	purge				2-60													40S-15		

DIVER NO.	NOVEMBER 1985								DECEMBER 1985											
	11-14	11-15	11-18	11-19	11-20	11-25	11-26	11-27	12-2	12-3	12-04	12-5	12-6	12-9	12-10	12-11	12-12	12-13	12-16	12-17
17			3-45*												40S-15(M)					
18				2-30 (D)												40S-15(M)				
19	purge		2-30*							40M-15										
20						2-60														
21					2-60												40S-15			
22		purge				2-60										40S-15(M)				
23	purge	purge	2-30			2-60														
24	purge	purge	2-30			2-60		3-90						40S-15(M)				40S-15		40S-15
25		purge			2-60					40M-15				40S-15(M)						
26	purge		2-30			2-60		3-90*			40M-15 (P)				40S-15(M)			40S-15		
27	purge		2-30			2-60				40M-15			40S-15(M)				40S-15			
28	purge	purge	2-30			2-60		3-90				40M-15								
29	purge		2-30			2-60				40M-15				40S-15(M)			40S-15		40S-15	40S-15
30	purge	purge	2-30 (C)				2-60													
31	purge	purge	2-30			2-60		3-90*		40M-15						40S-15(M)		40S-15		

DIVER NO.	NOVEMBER 1985								DECEMBER 1985											
	11-14	11-15	11-18	11-19	11-20	11-25	11-26	11-27	12-2	12-3	12-04	12-5	12-6	12-9	12-10	12-11	12-12	12-13	12-16	12-17
32	purge	purge	2-30				2-60			40M-15			40S-15(M)	40S-15(M)			40S-15			
33		purge			2-60					40M-15			40S-15(M)			40S-15(M)			40S-15	
34		purge			2-60	2-60	2-60				40M-15		40S-15(M)	40S-15(M)			40S-15		40S-15	
35		purge			2-60	2-60	2-60													
36		purge			2-60		2-60				40M-15 (P)								40S-15	
37	purge	purge			2-60		2-60 (P)												40S-15	
38	purge	purge		2-30			2-60*		3-90		40M-15				40S-15(M)			40S-15		40S-15
39	purge			2-30	2-60		2-60*		3-90 (P)				40S-15(M)							
40	purge	purge	2-30			2-60				40M-15				40S-15(M)		40S-15(M)			40S-15	
41	purge			2-30 (D)		2-60		3-90							40S-15(M)					40S-15
42	purge		2-30			2-60 (D)					40M-15 (D)				40S-15(M) (D)		OTT	OTT	OTT	OTT
43	purge				2-60			3-90*				40M-15				40S-15(M)			40S-15	
44	purge	purge			2-60				3-90		40M-15			40S-15(M)				40S-15		40S-15
45	purge			3-45*			2-60		3-90*							40S-15(M)		40S-15		40S-15
46	purge	purge									40M-15				40S-15(M)		40S-15			
47	purge								3-90*				40S-15(M)		40S-15(M)			40S-15	40S-15	
48				3-45 (D)					3-90 (D)								OTT	OTT	OTT	OTT

NOTES:

(1) An asterisk (*) after the profile number indicates that the diver neither completed the profile nor experienced a toxicity episode, but was stopped for safety reasons due to another diver suffering a toxicity episode.

(2) The letter (C), (D), (P) below the profile number indicate a toxicity episode on that profile--a Convulsion, Definite, or Probable episode, respectively.

(3) "OTT" refers to a standard U.S. Navy Oxygen Tolerance Test.

(4) "Purge" refers to an experimental dive to test the new Underwater Purge Procedure being developed for the Draeger LAR V. The results of these dives are described in NEDU Report 6-86.