Testing of revised unlimited-duration upward excursions during helium-oxygen saturation dives

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Thalmann ED. Testing of revised unlimited-duration upward excursions during helium-oxygen saturation dives. Undersea Biomed Res 1989; 16(3):195–218.—As originally published in 1978, the U.S. Navy Unlimited-Duration Saturation Excursion Limits were found to result in an occasional case of vestibular decompression sickness (DCS) after upward excursions from storage depths in the 800–1000 feet of seawater (fsw) range. A series of dives was undertaken to revise these limits. Fifty divers performed a total of 164 man-excursions during 9 saturation dives with maximum storage depths of 36 to 1100 fsw. All excursions tested were upward excursions taken after saturation at the initial storage depth. A total of 130 man-excursions were at or greater than the maximum limits, which were calculated according to the empirical relationship:

$$UEXD = [(0.1574 \cdot D_1 + 6.197)^{0.5} - 1]/(0.0787)$$

where UEXD is the upward excursion distance and D_1 is the pre-excursion storage depth in fsw. During testing, 9 cases of DCS occurred that were all type 1. All of these cases occurred 8 h or more into the saturation decompression, which was begun immediately after some of the upward excursions. None of these cases of DCS were ascribed to the excursion itself, but rather to a saturation decompression rate that was too fast. As a result of the described testing, excursions computed according to the above formula were accepted for operational use in 1987. The theoretical aspects of the excursion distance calculation are discussed, including the compatibility with some current decompression models.

saturation diving
decompression
saturation excursions
upward excursions
mathematical modeling
decompression sickness

The concept of unlimited-duration saturation excursions holds that after complete saturation at some initial storage depth (D_1) there is some shallower depth (D_2) to which the diver could immediately ascend without suffering symptoms of decompression sickness (DCS). This means that not only could a diver saturated at D_1 ascend immediately to D_2, but that a diver saturated at D_2 should be able to make downward excursions of any frequency and duration to the corresponding D_1. A diver saturated at a depth between a D_1, D_2 pair could make upward excursions to D_2 and downward excursions to D_1 of any frequency or duration.

The first set of U.S. Navy Unlimited-Duration Excursion Tables were published in 1978 (1) based on a series of dives done at the U.S. Navy Experimental Diving Unit (NEDU) in Panama City, FL. These excursion tables were based on a linear relationship between D_1 and D_2 for depths in feet of seawater (fsw):

$$D_1 = 51.49 + 1.1567 \cdot D_2 \qquad (1)$$

The tested limits of these initial excursion tables were a 180-fsw upward excursion from 1000 fsw (D_2 = 820 fsw) and a 75-fsw upward excursion from 225 fsw (D_2 = 150 fsw) with ascent rates of 60 fsw/min. Excursions to depths shallower than 150 fsw or from depths deeper than 1000 fsw were not permitted. As a result of several reported cases of DCS from Fleet use of these limits in the 800-fsw range, the above excursion limits were revised in 1980 according to the following relationship:

$$D_1 = 49.20 + 1.139 \cdot D_2 \qquad (2)$$

This reduced the excursion distance from 1000 to 165 fsw (D_2 = 835 fsw) and the shallowest excursion was reduced to 70 fsw from a depth of 220 fsw (D_2 = 150 fsw). These revised limits were published in the 1981 revision of volume 2 of the U.S. Navy Diving Manual (2) and were used in their metric form by the Royal Navy in Great Britain. The procedures accompanying these excursion tables allowed upward excursions to be made based solely on the deepest depth ever attained at any time during a dive. This meant that if the divers attained a depth of 1000 fsw at any time during a dive and made a several-day stop at 750 fsw they would not be able to make any upward excursions because the upward excursion limit from 1000 fsw is 850 fsw. This obviously restrictive policy was implemented because no studies were done during the initial development of these limits to establish the minimum interexcursion time before a subsequent upward excursion to the limits of the tables could be performed.

The revised excursion limits based on Eq. *2* were used on 2, 1000 fsw dives done at NEDU in 1980 and 1981. On each dive, 1 of the 6 divers who made the 165-fsw upward excursion from 1000 fsw (ascent rate 60 fsw/min) suffered symptoms of inner ear DCS (nausea, vertigo, unsteadiness, and nystagmus) within 60 min of completing the excursion. Immediate recompression to 1000 fsw relieved all symptoms within 5 min. On a subsequent dive at NEDU in 1981 a reduced 156-fsw upward excursion was made from 1000 fsw and 1 of the 6 divers reported knee pain 3 h after arriving at 844 fsw where a 36-h hold was planned.

As a result of these three instances of DCS a further revision of the unlimited-duration upward excursion limits was felt to be in order. In addition to looking at the excursion limits it was also decided to investigate the minimum period that must be spent at any post-excursion depth before a subsequent maximum upward excursion could be made. This paper describes the results of some 164 man-excursions done during 9 saturation dives performed by both the U.S. Navy and the Royal Navy between February 1984 and June 1987. The excursion limits resulting from these dives are now operational procedures in both navies.

METHODS

Dives were done either at shore-based chamber facilities or during open-sea operations. Shore-based dives were done either at NEDU or at the Admiralty Research

Establishment (Physiological Laboratory) [ARE(PL)] in Alverstoke, Great Britain. Open-sea dives were done during salvage or diver training operations from the diving vessel MV *Seaforth Clansman* by the members of the Royal Navy diving party assigned to the ship, which was under charter to the Royal Navy. A total of 50 divers participated in the study, all members of the U.S. Navy, Royal Navy, Canadian Forces, or Royal Australian Navy. They had received a thorough diving physical examination within the previous year.

All dives are summarized in Table 1. Except for the October 1986 ARE(PL) dive, all dives began with compression on air to approximately 2 ATA followed by compression to depth on 100% helium, following standard U.S. Navy and Royal Navy operating procedures. The October 1986 ARE(PL) dive included studies during the compression phase, which required that as much nitrogen as possible be eliminated from the chamber at 1 ATA before compression on 100% helium. No attempt was made to control nitrogen partial pressure in any of the dives, but where analysis was done the pre-excursion partial pressure of nitrogen is given in Table 1. Where multiple analyses were done, the range of values in the 48 h immediately preceding the upward excursion is given. The oxygen partial pressure was maintained at 0.42 ± 0.01 ATA, except for the April–May 1987 *Clansman* dive that used a partial pressure of 0.50 ± 0.01 ATA. The oxygen partial pressure was allowed to fall from these pre-excursion values as a result of the upward excursions. Oxygen was not added to the chamber until the post-excursion depth was reached, and reestablishment to the pre-excursion partial pressure took 30–60 min.

A total of 34 of the man-excursions shown in Table 1 (footnotes *H* and *P*) were not at the maximum limits under consideration. Operational considerations dictated that the first excursion on the May 1986 NEDU dive be less than the maximum limits, and all 3 of the *Clansman* dives had multiple in-water downward excursions whose distances and durations were dictated by the salvage or training operation going on at the time.

To ensure that the in-water downward excursions done during the *Clansman* dives did not influence the subsequent upward excursion, a hold at the pre-excursion storage depth was taken to allow resaturation. This hold was 24–48 h, depending on the number and length of in-water excursions as noted in Table 1 footnotes. In the case of the shore-based chamber dives there was usually some in-water wetpot work with divers 5–7 fsw below the pre-excursion storage depth for periods of 2–6 h. No compensation was made for these, and in some cases the upward excursion was made within a few hours after the last diver completed his in-water work.

Upward excursion rates were 60 fsw/min for excursions below 150 fsw. For shallower excursions, the rate was limited to 30–40 fsw/min by the maximum depressurization rate of the chamber at the particular depth. During the upward excursion all divers sat quietly in full view of each other and the outside chamber crew via closed-circuit television. They remained seated for a 2-h post-excursion observation period, at which point they resumed normal activity.

In all dives the upward excursions and subsequent decompression were done in a dry living chamber with the divers at rest. Carbon dioxide partial pressure was kept below 4 mmHg, and chamber temperature and humidity were adjusted to diver comfort. No attempt was made to control chamber temperature during upward excursions, which fell to as low as 20°C during the deeper excursions. Divers kept warm

TABLE 1

SUMMARY OF TESTED UPWARD EXCURSIONS FROM FEBRUARY 1984 TO JUNE 1987

Date and Facility	Excursion, fsw	Decompression (A)	Time at Pre-excursion Depth	No. Divers	Pre-excursion (B) P_{N_2} (ATA)	P_{O_2} (ATA)	DCS/Time Post-excursion (C)
Feb 1984	850 → 712	6 fsw/h (D)	6 days	7	not measured	0.42	1/11 h
NEDU	650 → 530	6 fsw/h (E)	84 h	7		±0.01	0
	200 → 134	5 fsw/h (F)	96 h	7			0
Mar–Apr 1985	644 → 525	hold	18 days	6	0.25–0.18	0.42	0
NEDU	525 → 418	3.80 fsw/h (G)	48 h	6	0.18–0.13	±0.01	0
May 1985	1000 → 850	3.80 fsw/h	90 h	6	1.05–0.86	0.42	0
NEDU	844 → 707	3.80 fsw/h	13 days	6	0.31–0.31	±0.01	0
	644 → 525	3.80 fsw/h	48 h	6	0.23–0.28		0
	130 → 77	3.80 fsw/h (G)	48 h	6	0.08–0.07		0
May 1986	1100 → 994 (H)	hold	5 days	6 (H)	1.21–1.17	0.42	0
NEDU	994 → 844	hold	4 days	6	0.54–0.47	±0.01	0
	844 → 706	3.80 fsw/h	90 h	6	0.28–0.24		3/18 h
	644 → 525	hold	48 h	6	0.28–0.25		0
	525 → 418	3.80 fsw/h	48 h	6	0.17–0.16		0
	294 → 214	3.80 fsw/h (G)	114 h	6	0.11–0.12		1/8 h
Oct 1986	979 → 829	3.63 fsw/h	13 days	3	0.06–0.07	0.42	0
ARE (PL)	78 → 36	hold	48 h	3	0.04–0.03	±0.01	0
	36 → 5	2.72 fsw/h (G)	48 h	3	0.03–0.02		0
Jan 1987	963 ↔ 815 (P)	hold	mult. 4–6 h (I)	6 (P)	0.81	0.42	0
Clansman	815 → 679	3.63 fsw/h (G)	48 h	6	0.81	±0.01	1/175 h
Mar 1987	206 ↔ 147 (P)	hold	mult. 4–6 h (J)	6 (P)		0.42	0
Clansman	147 → 88	3.26 fsw/h (G)	42 h	6	0.18	±0.01	1/11 h
	190 ↔ 144 (P)	hold	mult. 2–3 h (K)	4 (P)		0.42	0
	144 → 85	2.80 fsw/h (G)	24 h	4		±0.01	0

Apr–May 1987	228 ↔ 147 (P)	hold	mult. 5–6 h (L)	4 (P)		0.50	0
Clansman	147 → 88	2.80 fsw/h (M)	31 h	4	1.15	±0.01	1/26 h
	182 ↔ 147 (P)	hold	mult. 2–3 h (N)	8 (P)		0.50	0
	147 → 88	2.61 fsw/h (M)	38 h	8	1.11	±0.01	0
Jun 1987	281 → 202	2.61 fsw/h (O)	67 h	6	1.19–0.97	0.42	1/79 h
ARE (PL)						±0.01	

Key:

(A) Shows decompression rate begun immediately after completing upward excursion to next shallower storage depth. Indicated rate maintained continuously without stops to next shallower depth unless noted otherwise.
(B) If more than one value shown the first value is for 48 h preceding upward excursion.
(C) All DCS was type 1.
(D) Decompression immediately commenced to 620 fsw with a 2-h stop at 667 fsw. DCS occurred after 6 h at 620 fsw. Stricken diver and one other recompressed to 650 fsw from 620 fsw, with remaining divers staying at 620 fsw 24 h before being compressed to meet other divers at 650 fsw to complete equipment studies.
(E) Stop at 1400–1600 at 485 fsw. Thereafter stops at 0000–0600 and 1400–1600 daily.
(F) Standard USN saturation decompression (6 fsw/h to 200 fsw; 5 fsw/h to 100 fsw; 4 fsw/h to 50 fsw; 3 fsw/h to surface. Stops at 0000–0600 and 1400–1600 daily).
(G) Rate progressively slowed shallower than 40 fsw to compensate for drop in Po_2 at maximum Fo_2 of 19.0%.
(H) Excursion not at maximum depth limits.
(I) Multiple in-water downward excursions during the 48 h preceding start of 48 h hold at 815 fsw.
(J) Multiple in-water downward excursions during the 28 h preceding start of 42 h hold at 147 fsw.
(K) Multiple in-water downward excursions during the 14 h preceding start of 24 h hold at 144 fsw.
(L) Multiple in-water downward excursions during the 84 h preceding start of 31 h hold at 147 fsw.
(M) Rate progressively slowed shallower than 33 fsw to compensate for drop in Po_2 at maximum Fo_2 of 25.0%.
(N) Multiple in-water downward excursions during the 17 h preceding start of 38 h hold at 147 fsw.
(O) Rate progressively slowed shallower than 23 fsw to compensate for drop in Po_2 at maximum Fo_2 of 25.0%.
(P) Time at pre-excursion depth 6 h or less, not at maximum time limits.

by wrapping themselves in blankets until the chamber was rewarmed to a comfortable temperature, which took no more than 60 min.

The number of divers participating in each dive is shown in Table 1, and with the exception of 2 of the *Clansman* dives, which were conducted in two phases, all divers in a given dive made all of the excursions shown. On the March 1987 *Clansman* dive, 4 of the 6 divers who made the excursions during the first phase were recompressed (for reasons discussed later) before reaching the surface and performed the excursions shown in the second phase below the *broken line*, Table 1. In contrast, a total of 12 divers participated in the second *Clansman* dive, each diver making only one upward excursion from 147 fsw. Eight of the 50 divers participated in 2 dives. Single divers participated in the following 5 pairs of dives: February 1984, March–April 1985; February 1984, May 1986; March –April 1985, May 1986; January 1987, April–May 1987; October 1986, January 1987. Three other divers from the January 1987 dive also made the March 1987 dive.

Some upward excursions were followed immediately by saturation decompression at the rates shown in Table 1. With the exception of the first dive, which used standard USN saturation decompression procedures, all decompressions were experimental and the details given below are all that are pertinent to the upward excursions, which comprise the subject of this paper. Further details regarding the experimental decompression will be left to a future paper.

The experimental decompressions were all carried out at the specified mean rate continuously 24 h/day. All depths in Table 1 have been converted to fsw[1] and depending on the depth units in use at the time stops were taken every 10 fsw (e.g., 3.80 fsw/h = 158-min stops) or every 3 meters of seawater (msw) (e.g., 3.63 fsw/h = 162-min stops). The stop-depth increment was decreased to 5 fsw (1 msw) shallower than 40 fsw (12 msw). When the oxygen fraction reached its maximum allowable level (19 or 25%, *see* Table 1), stop times were progressively increased to compensate for the fall in oxygen partial pressure.

Calculation of upward excursions

The relationship used to calculate excursion distances was based on an empirical relationship suggested by Behnke (3). It was modified to the form:

$$\text{UEXD} = (5.04/\text{CF}) \cdot (D_2 \cdot \text{CF} + 33)^{0.5} \qquad (3)$$

where:

UEXD = upward excursion distance
D_2 = postexcursion depth
CF = depth conversion factor
(1.0 if all depths in fsw)
(3.26394 if all depths in msw)

(*see* footnote 1).

A full description of the derivation of Eq. *3* is given later. Excursion distances can be calculated using the pre-excursion storage depth (D_1) by substitution of the rela-

[1]Conversions between depth in meters of seawater (msw) and feet of seawater (fsw) take into account the different specific gravities assumed for seawater in the United States (1.02500) and Europe (1.01972 or 1 bar = 10 msw). The conversion factor from meters to feet (3.28084) is multiplied by the specific gravity ratio (1.01972:1.02500) to obtain the conversion factor that converts dry chamber depths in msw to depths of an equivalent pressure in fsw (3.26394).

tionship $D_2 = D_1 - UEXD$ into Eq. *3* and solving the resulting quadratic equation for D_1:

$$UEXD = [(0.1574 \cdot D_1 \cdot CF + 6.197)^{0.5} - 1]/(0.0787 \cdot CF) \qquad (4)$$

All upward excursions tested as described in this paper were computed based on the pre-excursion storage depth (D_1) using Eq. *4* and rounding the resultant excursion distance up to the next greater foot or meter.

The final excursion limits as used operationally are given in the appendix. Table 1 *A*, *B* give excursion distances for excursions shallower than the storage depth, which were calculated using Eq. *4*, with D_1 being given the values in the storage depth column. Table 2 *A*, *B* give distances for excursions deeper than storage depth, and these were calculated using Eq. *3*, with D_2 being given the values of storage depth. The resultant value for excursion distance was rounded by adding the factor 0.33/CF and truncating the result to give an integer value.

RESULTS

Of the 164 man-excursions performed (Table 1), a total of 130 were equal to or greater than the final operational limits (Table 2). All 9 cases of DCS that resulted were type 1 and occurred 8 h or more after completion of the upward excursion during the subsequent saturation decompression. A total of six excursions (30 man-excursions) were "paired," that is, a 48-h hold was taken at the post-excursion depth followed immediately by another upward excursion (644 → 525, 525 → 418 on the March–April 1985 and May 1986 dives, and 78 → 36, 36 → 5 on the October 1986 dive). A further four excursions (24 man-excursions) were "near paired." After the first upward excursion, a short period of decompression (<16 h) to a slightly shallower depth took place, at which point a 48-h hold was taken before performing the second excursion of the pair (844 → 707, 644 → 525 on the May 1985 dive and 844 → 706, 644 → 525 on the May 1986 dive). One paired excursion began after a 48-h hold following 206 h of saturation decompression (78 → 36, 36 → 5 on the October 1986 dive).

With a single exception, all divers spent at least 48 h at or deeper than the pre-excursion storage depth. With the exception of the *Clansman* dives, the length of time at the pre-excursion depth is given in the *Time at pre-excursion depth* column of Table 1. During the three *Clansman* dives, an initial period was spent doing in-water downward excursions (Table 1, footnotes *I–L, N*) followed by a hold at exactly the pre-excursion depth (Table 1 *Time at pre-excursion depth*). The only instance where the sum of these two times was less than 48 h was the March 1987 *Clansman* dives where all 6 divers were decompressing from the first dive when DCS developed in 1 diver at 52 fsw. At that time, the salvage operation required further in-water diving; therefore, the stricken diver and 3 fellow divers were recompressed to 144 fsw while the 2 remaining divers continued decompression to the surface. The 4 divers who had been recompressed then began the second phase of the dive shown below the *broken line,* Table 1, spending 14 h doing in-water downward excursions followed by a 24-h hold at 144 fsw before commencing the upward excursion and saturation decompression.

TABLE 2
SUMMARY OF EXCURSIONS TESTED AT OR EXCEEDING FINAL OPERATIONAL LIMITS[a]

D_1, fsw	D_2, fsw	Excursion Distance, fsw		Number of Man Exposures	
		Tested	Final Limit[b]	Ungrouped	Grouped
1000	850	150	150	6	
994	844	150	149	6	
979	829	150	148	3	
850	712	138	137	7	40
844	707	137	137	6	
844	706	138	137	6	
815	679	136	134	6	
650	530	120	119	7	
644	525	119	119	18	37
525	418	107	106	12	
294	214	80	79	6	
281	202	78	77	6	19
200	134	66	65	7	
147	88	59	55	18	
144	85	59	55	4	
130	77	53	53	6	34
78	36	42	40	3	
36	5	31	29	3	

[a]Data summarized from Table 1. [b]Final operational limit as determined from D_1 using rules and limits in the appendix.

All DCS was pain-only and involved the knee joint, except for 2 cases. The shoulder joint was involved in the case occurring 114 h after the 294 → 214 fsw excursion on the May 1986 dive and in the case occurring 175 h after completion of the upward excursion on the January 1987 dive. All symptoms responded with complete relief with minimal recompression.

DISCUSSION

In evaluating the results of this study there are two aspects that must be considered: the operational and theoretical. The operational aspect considers only whether Eqs. *3* and *4* predict safe upward excursions over the depth range considered and whether further increases in excursion distances are practical. The theoretical aspect considers how the data presented in Table 1 fit in with the current concepts of decompression and whether it sheds any new light on our knowledge. Since the driving force behind the study was to solve an operational problem, this aspect will be discussed first.

Operational aspects

The dives performed in this series contained various combinations of upward excursions, holds, and saturation decompressions. Dive profiles were sometimes dictated by operational considerations, and opportunities were not always available to take a post-excursion hold of sufficient length to verify that DCS would not result from the upward excursion. It was fully realized throughout the study that upward excursions may influence the subsequent saturation decompression and that DCS arising during decompression may not have occurred if the preceding upward excursion had not been performed. It must be clearly understood that this paper does not address the interaction of the upward excursion and the subsequent decompression, this will be left for future endeavors. The only issue that needs to be resolved here is whether any of the 9 cases of type 1 DCS that did occur were a direct result of the magnitude of the excursion; that is, would they have occurred had a post-excursion depth hold of sufficient length been taken. In the study describing the development of the original Unlimited-Duration Saturation Excursion Limits, a post-excursion observation period of 8 h was assumed to be sufficient to verify that DCS would not result following the excursion (1). In that same study, 3 cases of type I DCS occurred following the upward excursions; the only one that was ascribed to the excursion itself occurred 4.5 h post-excursion. Since all cases of DCS in this study occurred 8 h or more after the excursion, these cases would not be ascribed to the excursion itself by the criteria used in developing the original Unlimited-Duration Saturation Excursion Limits.

Three of the cases of DCS from Table 1 (January 1987, April–May 1987, and June 1987) occurred more than 24 h post-excursion, a time long enough to make it difficult to ascribe the symptoms solely to the upward excursion. Looking at shorter intervals, 1 diver suffered DCS 11 h after making a 59-fsw upward excursion from 147 fsw during the March 1987 *Clansman* dive (Table 1). At that time he was being decompressed at 3.26 fsw/h. He was recompressed (with complete relief), and 38 h later made an identical upward excursion from 144 fsw and decompressed at a slower rate of 2.80 fsw/h without incident. While a single case of DCS occurred 8 h after the 294 → 214 fsw excursion on the May 1986 dive during the 3.80 fsw/h decompression, no DCS occurred on a similar 281 → 202 fsw excursion in June 1987 when the rate of subsequent decompression was reduced to 2.61 fsw/h. So in these latter two instances, DCS incidence was reduced when the post-excursion decompression rate was reduced.

The excursion from 850 and 844 fsw done during the February 1984 and May 1986 dives resulted in DCS 11 and 18 h post-excursion during saturation decompression. However, an almost identical excursion from 844 fsw done in May 1986 produced no DCS when followed by a 13-h hold at the post-excursion depth.

It was concluded from the above evidence that all 9 cases of DCS that occurred in this study were due to a post-excursion saturation decompression rate that was too fast and were not a direct result of upward excursion distances being too large. It thus becomes a matter of reducing the post-excursion decompression rate to avoid DCS rather than reducing the excursion distances.

Since there were no cases of DCS that could be ascribed to the upward excursions themselves, one could ask if the excursion distances as computed by Eqs. *3* and *4* will be overly conservative; that is, could significant increases in upward excursion distances be safely accomplished? Table 3 documents all saturation excursions done at NEDU from 1976 to the start of this study. Dives below the *broken line* were those

TABLE 3

UPWARD EXCURSIONS DONE AT NEDU FROM AUGUST 1976 TO NOVEMBER 1982[a]

Date	Excursion, fsw	Decompression (A)	Time at Pre-excursion Depth, h	No. Divers	DCS/Time Post-excursion (B)
Aug 1976	1208 → 1020	16 h hold ↓	20	6	0
	1208 → 1000	3 h hold ↓	24	6	0
	1400 → 1180	16 h hold ↓	93	6	0
	1400 → 1166	16 h hold ↓	80	6	0
	1400 → 1166	STD USN	48	6	1/3 h (C)
Jan 1977	450 → 380 (D)	hold	114	6	0
Aug 1977	273 → 200 (D)	hold	8	4	0
Nov 1977	1208 → 1000	STD USN	24	6	1/5 h
(maximum depth of dive 1500 fsw)					
Jun 1978	380 → 300 (D)	hold	160	6	0
Jul 1978	310 → 222 (E)	hold	196	6	0
Sep 1978	450 → 345	STD USN	96	6	1/>24 h
Jan 1979	1000 → 820	STD USN	64	6	1/>12 h
Apr 1979	640 → 517	STD USN	168	6	2/60 min (F)
Mar 1980	305 → 220 (E)	STD USN	120	6	0
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Nov 1980	1000 → 835 (G)	STD USN	119	6	1/<60 min (H)
Jul 1981	1000 → 835 (G)	STD USN	102	6	1/35 min (H)
Nov 1982	1000 → 844 (I)	36 h hold	94	6	1/3 h
	844 → 698	STD USN	36	4	1/50 min (H)

[a]PO_2 0.35–0.40 ATA.

Key:

(A)—"hold ↓" Indicates length of hold before compression to deeper depth. "STD USN" indicates standard USN saturation decompression begun immediately following excursion (6 fsw/h to 200 fsw; 5 fsw/h to 100 fsw; 4 fsw/h to 50 fsw; 3 fsw/h to surface. Stops at 0000–0600 and 1400–1600 daily).

(B)—DCS is type 1 unless otherwise noted.

(C)—Inner ear DCS treated with recompression to 1400 fsw. Multiple DCS during final stages of decompression.

(D)—Excursion is less than the limit allowed by the upward excursion table in use at the time.

(E)—Storage depth was 300 fsw. Indicated maximum depth was based on maximum in-water downward excursions lasting 4–6 h for equipment testing.

(F)—One case was inner ear DCS treated with recompression to 640 fsw.

(G)—1981 revised excursion limits.

(H)—Inner ear DCS treated with recompression to pre-excursion depth.

(I)—Excursion reduced from 1981 revised excursion limits (*see* text).

done after revision of the original 1978 limits. The 2 cases of inner ear DCS in 12 man-excursions on the November 1980 and July 1981 dives fairly well established that a 165 fsw upward excursion from 1000 fsw was unsafe. Even a reduced excursion of 156 fsw from 1000 fsw on the following dive produced type 1 DCS only 3 h post-excursion. Looking a bit shallower, 1 case of inner ear DCS occurred after a 640 → 517 fsw excursion on the April 1979 dive shown in Table 3. This excursion would be reduced 4 fsw using Eq. *4*, and there were some 25 DCS-free man-excursions done from storage depths of 650 to 644 fsw depths using the current limits (Table 1). Thus, any potential gains in excursion distances in the 650–1000 fsw range would seem to be less than 4 fsw.

At shallower depths, Tables 1 and 3 contain no data that would indicate how close to the DCS threshold the excursion limits predicted by Eq. *4* are. One starting point, however, is the saturation no-decompression limit, which is the depth at which direct ascent to 1 ATA is possible after complete saturation. The only published data in this regard appear in two NEDU reports. One report (4) describes 12-h exposures in which 5 subjects were exposed to increasing depths breathing 80% He:20% O_2 once a week until symptoms of DCS appeared. The symptom threshold depth was 36–50 fsw. One might debate whether 12 h is sufficient for complete saturation breathing helium-oxygen. Hempleman and Trotter (5) showed only a 10 fsw increase in the DCS threshold depth for no-decompression dives using a 4-h exposure time compared to a 2-h exposure. They concluded from this that saturation is essentially complete in 4 h. Also, in a series of unpublished helium-oxygen dives (breathing 80% He:20% O_2) done at ARE(PL) by Young, it was shown that there was little difference in the DCS threshold depth following 4- or 24-h exposures. The DCS threshold depth in this case was around 45 fsw. In the other NEDU report (6), the no-decompression curve out to 140 min breathing the same 80% He:20% O_2 mixture was determined and it appeared asymptotic to a depth of about 40 fsw. Taken together, one could conclude from the above observations that a depth of 36 fsw for the saturation no-decompression limit breathing 80% He:20% O_2 (Po_2 = 0.42 ATA) would be a reasonable estimate. Equation *3* predicts a saturation no-decompression limit of 29 fsw.

Barnard (7) looked at saturation excursions from the surface to 352 fsw breathing a 0.22 ATA oxygen in helium mixture. Divers were kept at the initial storage depth for 24 h and then were decompressed to the surface by taking a maximum upward excursion every 24 h. The deepest excursion attempted was from 352 to 225 fsw, which produced DCS, but a reduced excursion from 326 to 225 fsw was thought to be marginal. Table 4 shows the excursions that were felt by Barnard to be safe (converted from msw to fsw) and compares them with those predicted by the present study. Considering that the higher Po_2 of this study should allow at least as great an upward excursion as done by Barnard, one could only guess that the upward excursion from 153 fsw done in Barnard's study may have been too great. Otherwise, the excursions predicted by Eq. *3* are very similar to those believed safe by Barnard.

Additional information in this depth range can be obtained from the dives establishing the original USN upward excursion limits (1) in which a single case of type 1 DCS was observed in 1 of 6 divers during saturation decompression at 6 fsw/h approximately 4.5 h after completing a 225 → 150 fsw excursion. This case was attributed to the upward excursion by the investigators and they point out that the diver in question had been at 235 fsw for 2 of the 3 h immediately preceding the excursion. A total of 5 man-excursions were done from 230 → 150 fsw during the

TABLE 4
COMPARISON OF SAFE UPWARD EXCURSIONS FROM BARNARD'S STUDIES (6) WITH THOSE PREDICTED USING EQ. *4*

	Upward Excursion Distances, fsw	
Depth D_1, fsw	Barnard's Study, Po_2 = 0.22 ATA	Present Study Po_2 = 0.42 ATA
300	75	80
225	72	69
153	75	57
78	45	42
33	33	30

same study without incident. One might conclude that the DCS threshold at this depth is somewhere between 225 and 230 fsw for upward excursions to 150 fsw. Equation *3* puts the maximum initial storage depth for an upward excursion to 150 fsw at 218 fsw, some 7–12 fsw shallower.

Based on the above arguments, the excursion distances predicted by Eq. *3* or *4* could not be substantially increased from storage depths of 650 fsw or deeper. On the shallow end, an increase in the predicted saturation no-decompression depth from 29 to 36 fsw might be possible, as might a 7–12 fsw increase over the predicted excursion distance from 218 fsw. Operationally, these increases are small, and the operational limits proposed in the appendix are not felt to be particularly restrictive because of the small size of the potential gains.

Minimum inter-excursion time

The data of Barnard (7) would seem at first to indicate that a 24-h hold at a given depth was sufficient to allow a subsequent maximum upward excursion from depths of 225 fsw or shallower. However, closer examination of his results indicates that the length of this hold may have been the cause in some cases of DCS occurring on subsequent upward excursions from the next shallower storage depth. It was, therefore, felt prudent to try 36 h as the first inter-excursion time in this study. This was tried on the November 1982 dive (Table 3), where 4 of the 6 divers made the paired excursion from 1000 → 844 fsw and 844 → 698 with a 36-h hold intervening (the other 2 divers were the one suffering DCS and a tender from the first excursion). The single case of inner ear DCS occurring 50 min after the second excursion of the pair was considered sufficient cause to declare this interval unsafe and prompted extension of future trial inter-excursion intervals to 48 h.

In the present study, a total of 7 upward excursions resulting in 36 man-excursions were done with a 48-h hold between either paired excursions or between stopping saturation decompression and making a subsequent upward excursion (Table 1). These excursions were DCS-free, and while it was felt that an inter-excursion interval shorter than 48 h might be possible for shallower excursions, no time was available to test this assumption. Thus, the minimum inter-excursion 48-h hold was applied over the entire depth range in the final operational procedures.

Excursion limit safety

The excursions tested here were computed from a deterministic model. No continuous relationship between excursion distance and DCS incidence is implied, rather excursions are "safe" if they are equal to or less than the maximum limits or are "unsafe" if they exceed the limits. The purpose of this study was to access the degree of safety and to decide whether sufficient testing had been done to permit operational use of the tested limits.

In evaluating the results of a deterministic model with a binary outcome (DCS or no DCS), a formal statistical analysis can only be done by examining the binominal confidence limits for replicated samples. Table 2 summarizes replicated excursions, and while the observed 0% DCS incidence places the lower estimate of incidence at 0.0%, the range of the upper 95% limits were substantial, ranging from 70.8% for 3 man-excursions to 18.5% for 18 man-excursions. Grouping the data would reduce these upper 95% limits, but this could only be done rigorously if it could be established that DCS incidence was independent of D_1. Making this assumption over the entire depth range of this study is probably unwarranted but may be reasonable over small ranges of D_1. By grouping data as shown in Table 2, the upper estimate of DCS incidence is reduced to 9–10% for the shallowest and two deepest ranges, but remains high (17.7%) for the second shallowest.

Weathersby et al. (8) used a probabilistic model to analyze some 210 unlimited-duration upward excursions done before 1983. They were able to develop ~1 SE confidence bounds on excursion distances for a predicted DCS incidence of 5 and 10% over a 150- to 967-fsw depth range. These confidence limits were large and there was considerable overlap between the 5 and 10% predicted DCS incidence regions. The limits from this study would be less than the lower 1 SE confidence limit for a 10% incidence deep, and slightly above it, shallow. Shallower than approximately 300 fsw they would be very close to the upper 1 SE confidence limit for a 5% incidence, and well below it deeper than 300 fsw. Based on Weathersby's analysis, the best one could say is that the predicted DCS incidence for the excursion limits proposed here is probably between 5 and 10%, which is in reasonable agreement with the upper 10% bound for three of the four depth ranges shown in Table 2. However, this degree of uncertainty is too large to establish safety on purely statistical grounds, and it was deemed unlikely that sufficient experience could be gained during experimental dives to significantly reduce this uncertainty in a reasonable time.

Not being able to establish a reasonably certain DCS incidence, one could only make the qualitative estimate as to whether the excursions were "safe enough" for Fleet use. As with most other human decompression trials, this estimate was made by examination of raw incidences, comparisons with other trials, and judgment. Table 3 documents all of the saturation excursion experience at NEDU from the end of the evaluation dives for the initial upward excursion limits (1) to the beginning of the present study. In contrast to the results of this study, where there were no cases of DCS in the 130 man-excursions at the maximum limits, there were 6 cases in the 52 man-excursions done after July 1978 shown in Table 3, 4 being vestibular DCS. The 52 man-excursions before July 1978 were not considered because they were either less than the maximum allowable limits or were from depths greater than 1000 fsw. The original saturation excursion limits were accepted based on 100 man-excursions with pre-excursion exposure times of 24 h or more (1). This is in comparison to the

130 man-excursions at or exceeding the final limits of this study, which for the most part had pre-excursion exposure times in excess of 48 h. Based on this comparison, the above-mentioned reduction in raw incidence of vestibular DCS, and the absence of any DCS attributable to the upward excursions, it was judged that sufficient testing had been done to declare these new limits "safe enough" for Fleet use. Close monitoring of DCS occurrence during operational use will eventually establish the DCS incidence with more precision than could ever be obtained experimentally.

Theoretical aspects

Rationale behind equations (3) *and* (4)

It was the occurrence of vestibular DCS following some upward excursions as calculated by Eq. *1* that prompted the 1981 revision of the upward excursion limits. In this revision, the slope and intercept of the original linear relationship (Eq. *1*) were reduced (Eq. *2*), resulting in a 15-fsw reduction in excursion distance from the deepest D_1 (1000 fsw) and a 5-fsw reduction for the shallowest D_2 (150 fsw). At the beginning of the study reported here it was decided to further reduce the deepest upward excursion distance from 165 to 150 fsw and to extend the upward excursion limits to the surface. It was immediately obvious that simple extrapolation of Eq. *2* to the surface would not be useful because this would predict a saturation no-decompression limit of 49.20 fsw, which was considerably deeper than the 36-fsw depth suggested by published data (3–5), as discussed earlier.

Initially, maintaining the linear relationship between D_1 and D_2 was explored. In analyzing the dives done by Barnard (7), Hennessy and Hempleman (9) found that the D_1-D_2 relationship could be well approximated by a straight line with a slope of 1.397. This slope is considerably greater than the slope of the 1981 revised limits of 1.139 (Eq. *2*). A straight line through the D_1-D_2 pairs compatible with a 150 fsw upward excursion from 1000 fsw and a saturation no-decompression depth of 36 fsw (1000, 850; 36, 0) would reduce this slope even further to 1.134. It was felt that a single straight line would predict reasonable excursion distances only at its extremes, and that distances in the intermediate depth range would be overly conservative.

In 1979, Behnke (3) suggested that the original U.S. Navy Unlimited-Duration Upward Excursion Limits (1) could be predicted more accurately by an expression of the form:

$$\mathrm{UEXD} = K \cdot P_{\mathrm{min}}^{0.5} \qquad (5)$$

where:

P_{min} = absolute postexcursion pressure in fsw
K = empirical constant.

The value of K was calculated here by defining the maximum upward distance from 1000 fsw as 150 fsw (UEXD = 150 when P_{min} = 883). The resulting value of K was 5.04, which then gave a predicted value of 28.95 fsw for the saturation no-decompression limit. Based on evidence presented earlier, this is probably conservative but not felt to be overly restrictive. If one wanted to force the excursion limits through a presumed 36-fsw saturation no-decompression limit, it is possible to define a power function through both D_1-D_2 pairs (1000, 850) and (36, 0) resulting in the equation:

$$\text{UEXD} = 7.888 \cdot (D_2 + 33)^{0.434} \quad (6)$$

The attractiveness of Eq. *5* over Eq. *6* is that the former is a simple quadratic when expressed in terms of D_1 (Eq. *4*) making it very easy to handle mathematically. Equation *6* would require a series or interactive solution if expressed in terms of D_2. An additional factor was the lack of published exposures greater than 12 h in estimating the 36-fsw saturation no-decompression depth, and the value of 28.95 fsw as predicted by Eq. *3* was felt to be a reasonable starting point until a greater depth could be more firmly established. In the end, simplicity reigned and despite its shortcomings the relationship postulated by Behnke (Eq. *5*) was used with the constant *K* determined as above, resulting in Eq. *3*.

Decompression model compatibility

Based on the available saturation excursion data at the time, Hennessy and Hempleman (9) proposed an upward excursion model based on the assumption that the actual volume of gas that could be safely released from solution immediately after an upward excursion was constant. The reader is referred to the original work for a detailed description of the model, but the important thing is that it does predict a linear relationship between D_1 and D_2. As discussed earlier, a single straight line would not be a good fit to the data presented here, but Hennessy and Hempleman postulated that there were two tissues, each with its own slope and intercept, controlling ascents over various depth ranges. The tissue controlling deep excursions was postulated as aqueous "tight" tissue (vestibular apparatus), whereas the tissue controlling shallow excursions was postulated as fatty "loose" (knee joint). Postulating these two tissues would fit conceptually with the observation that inner ear DCS is most prevalent on excursions from the greater storage depths but rarely occurs from shallower storage depths. Examination of Tables 1 and 3 shows that DCS occurring after excursions from the shallower depths tended to have a late onset and was always type 1 (usually knee pain). This is in concert with the observations of Barnard (7), who noted knee pain as the predominant symptom when DCS occurred after his upward excursions from relatively shallow depths.

Equation *3* can be nicely approximated by two straight lines. The most straightforward method of doing this would be a least squares regression. However, one would rather ensure that excursions predicted by the straight-line approximation were less than those actually tested. Using D_1-D_2 pairs of 1000, 850, and 590, 476 will give a straight-line approximation for the deeper end of:

$$D_1 = 68.182 + 1.0963 \cdot D_2 \quad (7)$$

This will predict smaller upward excursion distances at the most 1 fsw less than that predicted by Eq. *3* over the range of storage depths from 590 to 1000 fsw. For the straight line describing the shallow end, the intercept will be the saturation no-decompression limit. The straight line

$$D_1 = 30.0 + 1.300 \cdot D_2 \quad (8)$$

has a saturation no-decompression limit close to that predicted by Eq. *3* and predicts smaller excursion distances no more than 1 fsw less than predicted by Eq. *3* down to a 225 fsw storage depth. Equation *3* also goes through the point 225, 150 which was the shallowest safe excursion tested in the original USN study (1).

Equations *7* and *8* will predict excursions larger than predicted by Eq. *3* in the 225–590 fsw storage depth range. The maximum difference will be where the two lines intersect, at the D_1-D_2 pair 273, 187. This is an 86 fsw upward excursion from 273 fsw, which is 11 fsw greater than predicted by Eq. *3*. No data from this study would attest to the safety of this larger excursion, but in a similar depth range Barnard (7) showed that a 326 → 225 fsw excursion was probably just below the DCS threshold, whereas Eq. *3* would have allowed an excursion to only 243 fsw. So, an 11-fsw increase in the upward excursion distance from 273 fsw may be safely attainable.

Equations *7* and *8* give an example of only one of a number of straight-line approximations to Eq. *3* under consideration. In determining which is the best two-straight-line approximation to Eq. *3*, one would have to include the concepts proposed by Hennessy and Hempleman (9) into a comprehensive decompression model, which predicts saturation excursion rates as well as upward excursion distances. The optimal fit would then be one that predicts not only safe upward excursion distances but also safe saturation decompression rates following these excursions.

Another decompression model that has appeared in the literature is the Bubble Formation Model of Yount (10, 11). This model predicts a linear relationship between D_1 and D_2 (12) down to approximately 300 fsw of:

$$D_1 = 23.32 + 1.372 \cdot D_2 \qquad (9)$$

Below a depth of 300 fsw the relationship becomes curvilinear, and the equations describing the relationship between D_1 and D_2 are not as simple or as easily manipulated as the straight lines proposed by Hennessy and Hempleman (9). However, a qualitative inspection of Yount's predictions for saturation excursions is compatible with the data from this study, especially at the deeper end of the depth spectrum. Yount's model VP3 (11) predicts approximately a 33-fsw reduction in the original 180-fsw upward excursion distance from 1000 fsw. This is close to the 30 fsw reduction of this study. Looking even deeper, Table 3 shows that the second time a 1400 → 1166 fsw excursion was attempted on the August 1986 dive a case of inner ear DCS resulted. Yount's model (11, 12) would have reduced this by approximately 52 fsw whereas Eq. *3* would have reduced it by 56 fsw. Yount's model (11, 12), however, does predict a no-decompression saturation limit of 23.32 fsw, which is even more conservative than that predicted by Eq. *3*. However, the fit with the data of this study is reasonable.

Overall, the decompression models discussed above are both compatible with the upward excursion data from the present study. Discriminating between these models will require a more definitive determination of the helium-oxygen saturation no-decompression limit, as well as examination of other aspects of the models, such as the saturation decompression rates that they predict.

Oxygen and nitrogen

During the initial development stages of decompression tables, oxygen was thought not to contribute to the development of DCS, and only inert gas tensions were considered in computations. In a series of experiments using goats, Eaton and Hempleman (12) showed that adding oxygen to air caused the DCS threshold to occur at a slightly lower nitrogen partial pressure, suggesting that oxygen was contributing to DCS occurrences. The range of the apparent contribution of oxygen to tissue gas tension compared to nitrogen in that study ranged from 100% (i.e., increasing inspired oxygen tension had the same effect as increasing nitrogen tension an equivalent amount) to 15% (i.e., increasing inspired oxygen tension increased tissue gas load only 15% as much as increasing nitrogen tension the same amount). The earlier decompression theories would have postulated a 0% effect (i.e., increasing inspired oxygen tension would have no effect on tissue gas tension).

More recently, Weathersby et al. (13) concluded from a human study comparing no-decompression depths for a fixed bottom time breathing various oxygen tensions in nitrogen that oxygen was less than 25% as potent as nitrogen in producing a risk of DCS. Increasing inspired oxygen tension from the 0.22 ATA used by Barnard (7) to the 0.42 ATA used in this study would increase the excursion distance 6.6 fsw if oxygen had a 0% effect, and to 5.0 fsw if it had a 25% effect (the upper limit described by Weathersby et al.). Thus, any gains in excursion distances that could be realized by increases in inspired oxygen tension would be small and probably insignificant compared to variations in individual susceptibility to DCS.

No attempt was made to quantitate oxygen effects on excursion distances in this study. Since the available evidence suggested that increasing oxygen partial pressure would increase excursion distances, rather than decrease them, excursions in this study were made under an assumed worst-case condition for oxygen. Operationally, chamber PO_2 is raised immediately before an upward excursion so that the PO_2 immediately after the excursion is no lower than 0.42 ATA. Also, when downward excursions are made, the PO_2 level in the underwater breathing apparatus is higher than 0.42 ATA. In this study excursions were made without increasing chamber PO_2, so in operational use the increased pre-excursion oxygen levels would add an increased degree of safety.

Nitrogen seems to decrease upward excursion distances, but the available evidence is by no means conclusive. The 12-h no-decompression limit breathing 80% He: 20% O_2 mixture is 3–14 fsw deeper than when breathing air (4). The saturation no-decompression depth on air seems to lie in the 23–26 fsw range (14), whereas a helium-oxygen mixture of a similar PO_2 would put this depth 30 fsw or deeper, as previously discussed. Breathing air, a 30-fsw upward excursion from 60 fsw (PO_2 = 0.59 ATA) was safe (15), compared to a 37-fsw limit allowed by Eq. *3* breathing helium-oxygen at a PO_2 of 0.42 ATA. Unfortunately, there is no evidence to indicate how close the 30 fsw air excursion was to the DCS threshold limit.

Operational constraints usually prevented controlling chamber nitrogen level to any specific level. However, the levels shown in Table 1 are believed to be representative of what would be found operationally, and the resultant excursions take these nitrogen levels into account. If the excursion limits presented here produce DCS in Fleet use, then chamber nitrogen partial pressure is one area that will have to be considered.

Effects of accommodation

Given that the testing of the original Unlimited-Duration Upward Excursion Limits (1) was not flawed in some way, one wonders why excursions that seemed safe during testing gave rise to DCS in actual use. One possible explanation is that the 24-h period assumed for complete saturation time was too short. Although sketchy, the available evidence as discussed earlier suggests that this is ample time for saturation (4–6). A more likely explanation is that the divers in the original study became accommodated to DCS. Dives in the original study had divers performing several upward and downward excursions on each dive, with only 8–12 h between excursions in some cases. Excursion testing also tended to progress from less severe to more severe excursions. It is possible that as excursions were performed, the divers became accommodated and were able to tolerate greater excursion distances without developing DCS than would unaccommodated divers. Hempleman (5) noted that in his experience "it was not prudent to introduce a team of new men on a procedure established as safe by a team of men who have been diving at frequent intervals." Thus, he would subject new divers to a series of work-up dives. Accommodation resulting in increased resistance to developing DCS has been documented most recently in a series of helium-oxygen fixed partial pressure bounce dives (16, 17). So, in retrospect, the original testing may have been done with accommodated divers producing excursion limits that were too great for unaccommodated divers.

The dives in this study attempted to prevent accommodation in two ways. In the first 5 dives and last dive shown in Table 1, the only upward excursions that were done occurred after spending at least 48 h at the pre-excursion depth. On the 3 *Clansman* dives, the multiple in-water downward excursions could not be prevented. However, the divers would not have made more than 2 of these in any 24-h period, and the pre-excursion hold was felt to reduce any carry-over of accommodation that may have occurred. The occurrence of accommodation in this study cannot be ruled out, but it is believed that the effect has been minimized as much as could be accomplished within the constraints imposed by operational considerations.

Operational use and DCS occurrence

Since the excursions in the appendix are now operational procedures, some estimate of their safety will become available as operational dives accumulate. However, the way these excursions are used operationally makes it unlikely that they will be tested at their limits. Usually, the storage depth chosen is shallower than the depth of the work site and downward excursions of only 6–8 h durations are made, which are much less than the 24 h or more allowed by unlimited duration excursions. Thus, lack of DCS occurring from these downward excursions will not attest to the safety of upward excursions made after saturation at the pre-excursion depth. Conversely, DCS resulting from excursions as usually performed in the Fleet would indicate that fairly substantial adjustments in the excursion limits might be required. This means that raw incidences of DCS resulting from excursions are of little value unless the excursion profile is precisely known and taken into consideration when compiling statistics.

CONCLUSIONS

1. Equations *3* and *4* predict safe unlimited-duration excursions from saturation breathing at least at 0.42 ATA P_{O_2} in helium.

2. A 48-h hold at a constant depth is sufficient to allow taking a subsequent upward excursion to the limits given in the appendix.
3. The excursion limits predicted by Eqs. *3* and *4* seem to be more conservative at the shallower storage depths.
4. Any gains in excursion distances compared to the limits in the appendix would be small and not significant operationally.
5. The data presented in this paper can be reasonably explained by at least two published decompression models, with no one model showing a clear advantage over the other.

The author acknowledges the dedication of all the Fleet divers whose participation allowed completion of the study. Special mention goes to the divers aboard the MV *Seaforth Clansman* whose lives would have been less complicated without experimental decompressions following open sea dives.

The opinions expressed in this paper are those of the author and should not be construed as representing official U.S. Navy or Royal Navy policy. Where official policy is noted, it has been explicitly stated as such.

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REFERENCES

1. Spaur WH, Thalmann, ED, Flynn ET, Zumrick JL, Reedy TW, Ringelberg JM. Development of unlimited duration excursion tables and procedures for helium-oxygen saturation diving. Undersea Biomed Res 1978; 5:159–177.
2. U.S. Navy Diving Manual, vol. 2. Mixed gas diving. Naval Sea Systems Command 0994-LP-001-9020, revised. Carson, CA, Best Bookbinders: 1981.
3. Behnke AR. The square-root principle in the calculation of one-stage (no-stop) decompression tables. Undersea Biomed Res 1979 6:357–365.
4. Duffner GJ, Snyder HH. Effects of exposing men to compressed air and helium oxygen mixtures for 12 hours at pressures of 2-2.6 atmospheres. Navy Experimental Diving Unit research report 1-59. Washington, DC: U.S. Navy Experimental Diving Unit, 1958.
5. Hempleman HV, Trotter C. Theoretical considerations underlying the deep diving experimental work during the period March 1964 to February 1965 at the Royal Naval Physiological Laboratory. Royal Naval Physiological Laboratory rep 3-65. Alverstoke: Admiralty Research Establishment, 1965.
6. Duffner GJ, Snyder JF, Smith LL. Adaption of helium-oxygen to mixed gas scuba. U.S. Navy Experimental Diving Unit research report 3-59. Washington, DC: U.S. Navy Experimental Diving Unit, 1959.
7. Barnard EEP. Fundamental studies in decompression from steady-state exposures. In: Lambertsen CJ, ed. Underwater physiology V. Proceedings of the fifth symposium on underwater physiology. Bethesda, MD: Federation of American Societies for Experimental Biology, 1976:263–271.
8. Weathersby PK, Homer LD, Flynn ET. On the likelihood of decompression sickness. J Appl Physiol 1984; 57:815–825.
9. Hennessy TR, Hempleman HV. An examination of the critical released gas volume concept in decompression sickness. Proc R Soc Lond B Biol Sci 1977; 197:299–313.
10. Yount DE. Application of a bubble formation model to decompression sickness in rats and humans. Aviat Space Environ Med 1979; 50:44–50.
11. Yount DE, Hoffman DC. On the use of a bubble formation model to calculate diving tables. Aviat Space Environ Med 1986; 57:149–156.
12. Eaton WJ, Hempleman HV. The role of oxygen in the aetiology of acute decompression sickness. Royal Navy Physiological Laboratory report 12-73. Alverstoke: Admiralty Research Establishment, 1973.
13. Weathersby PK, Hart BL, Flynn ET, Walker WF. Oxygen's role in human DCS after nitrogen-oxygen diving. Undersea Biomed Res 1987; 14 (Suppl):36.

14. Bell PY, Harrison JR, Page K, Summerfield M. An effect of CO_2 on the maximum safe decompression to 1 bar from oxygen-nitrogen saturation. Undersea Biomed Res 1986; 13:443–445.
15. Thalmann ED. Development of a 60 fsw air saturation decompression schedule. Undersea Biomed Res 1984; 11(Suppl):7.
16. Thalmann ED. Development of a decompression algorithm for constant 0.7 ATA oxygen partial pressure in helium diving. U.S. Navy Experimental Diving Unit report 1-85. Panama City: U.S. Navy Experimental Diving Unit, 1985.
17. Thalmann ED, Zumrick JL, Schwartz HJC, Butler FK. Accommodation to decompression sickness in HeO_2 divers. Undersea Biomed Res 1984; 11(Suppl):11.

Note:

Navy Experimental Diving Unit reports are available through the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

Royal Navy Physiological Laboratory reports can be obtained by writing to: Librarian, Admiralty Research Establishment (Alverstoke), Fort Road, Alverstoke, Gosport, Hampshire, England PO12 2DU.

APPENDIX

Unlimited duration upward excursions from a given storage depth are given in Table 1A (10 fsw increments) and Table 1B (3 msw increments).

Unlimited duration downward excursions from a given storage depth are given in Table 2A (10 fsw increments) and Table 2B (3 msw increments).

The storage depth used in finding upward excursion distances in Tables 1A and 1B is defined as the maximum depth attained at any time during the 48 h immediately preceding the upward excursion.

For storage depths between those shown, always use the excursion distance for the next *shallower* storage depth listed in the tables.

Excursions are made at a rate not exceeding 60 fsw (18 msw/min).

TABLE 1A

UNLIMITED DURATION SATURATION EXCURSION LIMITS FOR EXCURSIONS **SHALLOWER** THAN STORAGE DEPTH (DEPTH IN FSW)

Minimum P_{O_2} 0.42 ATA Depths in fsw					
Storage Depth, fsw	Minimum Depth, fsw	Excursion Distance, fsw	Storage Depth, fsw	Minimum Depth, fsw	Excursion Distance, fsw
29	0	29	520	414	106
30	1	29	530	423	107
40	8	32	540	432	108
50	15	35	550	440	110
60	23	37	560	449	111
70	30	40	570	458	112
80	38	42	580	467	113
90	46	44	590	476	114
100	53	47	600	485	115
110	61	49	610	494	116
120	69	51	620	503	117
130	77	53	630	512	118
140	85	55	640	521	119
150	94	56	650	531	119
160	102	58	660	540	120
170	110	60	670	549	121
180	118	62	680	558	122
190	127	63	690	567	123
200	135	65	700	576	124
210	143	67	710	585	125
220	152	68	720	594	126
230	160	70	730	603	127
240	169	71	740	612	128
250	177	73	750	621	129
260	186	74	760	630	130
270	194	76	770	639	131
280	203	77	780	649	131
290	211	79	790	658	132
300	220	80	800	667	133
310	229	81	810	676	134
320	237	83	820	685	135
330	246	84	830	694	136
340	255	85	840	703	137
350	263	87	850	713	137
360	272	88	860	722	138
370	281	89	870	731	139
380	290	90	880	740	140
390	298	92	890	749	141
400	307	93	900	758	142
410	316	94	910	768	142
420	325	95	920	777	143
430	334	96	930	786	144
440	343	97	940	795	145
450	351	99	950	804	146
460	360	100	960	814	146
470	369	101	970	823	147
480	378	102	980	832	148
490	387	103	990	841	149
500	396	104	1000	850	150
510	405	105			

TABLE 1B
UNLIMITED DURATION SATURATION EXCURSION LIMITS FOR EXCURSIONS **SHALLOWER** THAN STORAGE DEPTH (DEPTHS IN MSW)

Minimum P_{O_2} 0.42 ATA, msw					
Storage Depth, msw	Minimum Depth, msw	Excursion Distance, msw	Storage Depth, msw	Minimum Depth, msw	Excursion Distance, msw
8	0	8	162	129	33
9	0	9	165	132	33
12	3	9	168	135	33
15	5	10	171	138	33
18	7	11	174	140	34
21	9	12	177	143	34
24	12	12	180	146	34
27	14	13	183	148	35
30	16	14	186	151	35
33	19	14	189	154	35
36	21	15	192	156	36
39	23	16	195	159	36
42	26	16	198	162	36
45	28	17	201	165	36
48	31	17	204	167	37
51	33	18	207	170	37
54	36	18	210	173	37
57	38	19	213	175	38
60	41	19	216	178	38
63	43	20	219	181	38
66	46	20	222	184	38
69	48	21	225	186	39
72	51	21	228	189	39
75	53	22	231	192	39
78	56	22	234	195	39
81	58	23	237	197	40
84	61	23	240	200	40
87	64	23	243	203	40
90	66	24	246	205	41
93	69	24	249	208	41
96	71	25	252	211	41
99	74	25	255	214	41
102	76	26	258	216	42
105	79	26	261	219	42
108	82	26	264	222	42
111	84	27	267	225	42
114	87	27	270	227	43
117	90	27	273	230	43
120	92	28	276	233	43
123	95	28	279	236	43
126	98	28	282	238	44
129	100	29	285	241	44
132	103	29	288	244	44
135	105	30	291	247	44
138	108	30	294	249	45
141	111	30	297	252	45
144	113	31	300	255	45
147	116	31	303	258	45
150	119	31	306	261	45
153	121	32	309	263	46
156	124	32	312	266	46
159	127	32			

TABLE 2A

UNLIMITED DURATION SATURATION EXCURSION LIMITS FOR EXCURSIONS **DEEPER** THAN STORAGE DEPTH

Minimum Po_2 0.42 ATA					
Storage Depth, fsw	Maximum Depth, fsw	Excursion Distance, fsw	Storage Depth, fsw	Maximum Depth, fsw	Excursion Distance, fsw
0	29	29	430	538	108
10	43	33	440	549	109
20	57	37	450	561	111
30	70	40	460	572	112
40	83	43	470	583	113
50	96	46	480	594	114
60	108	48	490	605	115
70	121	51	500	616	116
80	133	53	510	627	117
90	146	56	520	638	118
100	158	58	530	649	119
110	170	60	540	660	120
120	182	62	550	672	122
130	194	64	560	683	123
140	206	66	570	694	124
150	218	68	580	705	125
160	230	70	590	716	126
170	242	72	600	727	127
180	253	73	610	738	128
190	265	75	620	749	129
200	277	77	630	760	130
210	288	78	640	771	131
220	300	80	650	782	132
230	312	82	660	793	133
240	323	83	670	803	133
250	335	85	680	814	134
260	346	86	690	825	135
270	358	88	700	836	136
280	369	89	710	847	137
290	380	90	720	858	138
300	392	92	730	869	139
310	403	93	740	880	140
320	415	95	750	891	141
330	426	96	760	902	142
340	437	97	770	913	143
350	448	98	780	924	144
360	460	100	790	934	144
370	471	101	800	945	145
380	482	102	810	956	146
390	493	103	820	967	147
400	505	105	830	978	148
410	516	106	840	989	149
420	527	107	850	1000	150

TABLE 2B

UNLIMITED DURATION SATURATION EXCURSION LIMITS FOR EXCURSIONS **DEEPER** THAN STORAGE DEPTH

Minimum P_{O_2} 0.425 Bar					
Storage Depth, msw	Maximum Depth, msw	Excursion Distance, msw	Storage Depth, msw	Maximum Depth, msw	Excursion Distance, msw
0	8	8	135	168	33
3	13	10	138	172	34
6	17	11	141	175	34
9	21	12	144	178	34
12	25	13	147	182	35
15	29	14	150	185	35
18	32	14	153	188	35
21	36	15	156	192	36
24	40	16	159	195	36
27	44	17	162	198	36
30	47	17	165	202	37
33	51	18	168	205	37
36	55	19	171	208	37
39	58	19	174	211	37
42	62	20	177	215	38
45	65	20	180	218	38
48	69	21	183	221	38
51	72	21	186	225	39
54	76	22	189	228	39
57	79	22	192	231	39
60	83	23	195	235	40
63	86	23	198	238	40
66	90	24	201	241	40
69	93	24	204	244	40
72	97	25	207	248	41
75	100	25	210	251	41
78	104	26	213	254	41
81	107	26	216	258	42
84	111	27	219	261	42
87	114	27	222	264	42
90	118	28	225	267	42
93	121	28	228	271	43
96	124	28	231	274	43
99	128	29	234	277	43
102	131	29	237	280	43
105	135	30	240	284	44
108	138	30	243	287	44
111	141	30	246	290	44
114	145	31	249	294	45
117	148	31	252	297	45
120	151	31	255	300	45
123	155	32	258	303	45
126	158	32	261	307	46
129	162	33	264	310	46
132	165	33	267	313	46