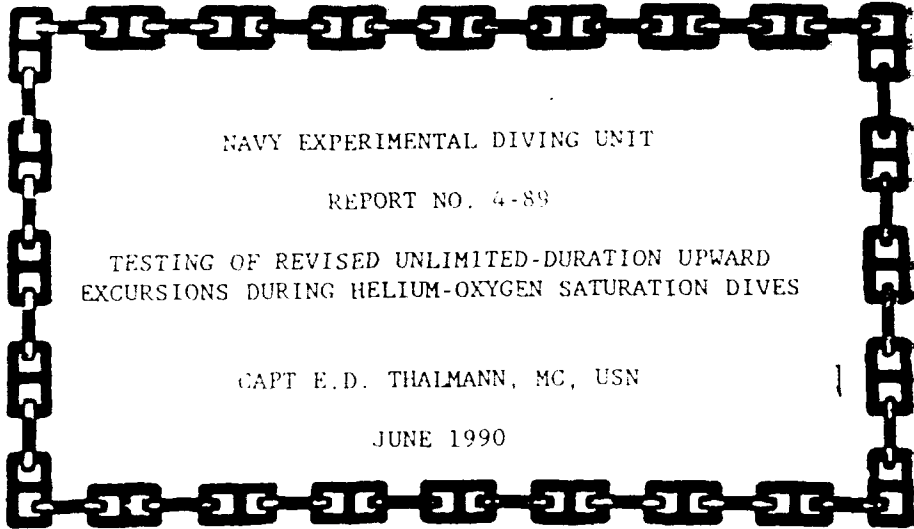


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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 4-89

TESTING OF REVISED UNLIMITED-DURATION UPWARD
EXCURSIONS DURING HELIUM-OXYGEN SATURATION DIVES

CAPT E.D. THALMANN, MC, USN

JUNE 1990

NAVY EXPERIMENTAL DIVING UNIT



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Submitted:

E.D. THALMANN
CAPT, MC, USN
Naval Medical Research
Institute

Reviewed:

H.J.C. SCHWARTZ
CAPT, MC, USN
Senior Medical Officer

Approved:

JAMES E. HALWACHS
CDR, USN
Commanding Officer

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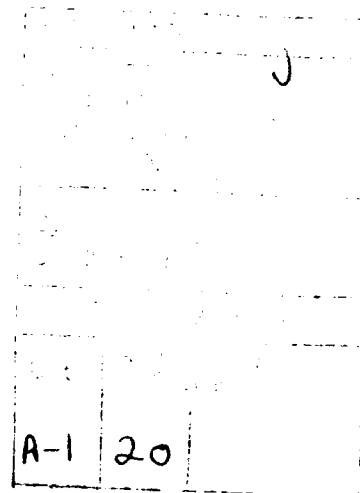
FORWARD

Revision of the Unlimited Duration Saturation Upward Excursions began as a project at the Navy Experimental Diving Unit (NEDU) in 1984. This project eventually expanded to include not only NEDU but two Ministry of Defence facilities in England. The author was stationed at NEDU up to October 1985 and then spent the following two years on exchange with the Royal Navy at the Institute of Naval Medicine in Gosport, England. During the period October 1985 - October 1987 the author personally oversaw the dives conducted in England by Royal Navy divers while the dive conducted at NEDU in 1986 was under the auspices of CAPT J. Zumrick and CAPT H.J.C. Schwartz.

The results of this 3-year trial were published in Undersea Biomedical Research 1989;16(3):195-218 and this report constitutes a reprint of that paper. These upward excursion limits were promulgated to the Fleet by the U.S. Navy in Volume Two, Revision Two, Mixed Gas Diving, October 1987 of the U.S. Navy Diving Manual and by the Royal Navy in Change 1, 1988 to BR 2806 (Supplement) Procedures for Deep and Saturation Diving.

Publication of this report did not occur until after the author's transfer from the Institute of Naval Medicine in England to the Naval Medical Research Institute in Bethesda, Maryland.

It must be emphasized that this study was a true cooperative effort between the Royal Navy and the U.S. Navy. This study could not have been completed without the full participation of both organizations.



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

E. D. THALMANN

Diving Medicine Department, Naval Medical Research Institute, Bethesda, Maryland 20814-5055

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:

$$\text{UEXD} = [(0.1574 \cdot D_1 + 6.197)^{0.75} - 1] / (0.0787)$$

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):

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

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:

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

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 I
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 _{N₂} (ATA) | Po ₂ (ATA) | DCS/Time Post-excursion (C) |
|----------------------|----------------|-------------------|-----------------------------|------------|--|-----------------------|-----------------------------|
| Feb 1984 NEDU | 850 → 712 | 6 fsw/h (D) | 6 days | 7 | not measured | 0.42 | 1/11 h |
| | 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 NEDU | 644 → 525 | hold | 18 days | 6 | 0.25-0.18 | 0.42 | 0 |
| | 525 → 418 | 3.80 fsw/h (G) | 48 h | 6 | 0.18-0.13 | ± 0.01 | 0 |
| May 1985 NEDU | 1000 → 850 | 3.80 fsw/h | 90 h | 6 | 1.05-0.86 | 0.42 | 0 |
| | 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 NEDU | 1100 → 994 (H) | hold | 5 days | 6 (H) | 1.21-1.17 | 0.42 | 0 |
| | 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 ARE (PL) | 979 → 829 | 3.63 fsw/h | 13 days | 3 | 0.06-0.07 | 0.42 | 0 |
| | 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 Clansman | 963 ↔ 815 (P) | hold | mult. 4-6 h (I) | 6 (P) | 0.81 | 0.42 | 0 |
| | 815 → 679 | 3.63 fsw/h (G) | 48 h | 6 | 0.81 | ± 0.01 | 1/175 f |
| Mar 1987 Clansman | 206 ↔ 147 (P) | hold | mult. 4-6 h (J) | 6 (P) | | 0.42 | 0 |
| | 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 | ± 0.01 | 1/26 h |
| | 182 ↔ 147 (P) | hold | mult. 2-3 h (N) | 8 P | 0.50 | 0 |
| Jun 1987 | 147 → 88 | 2.61 fsw/h (M) | 38 h | 4 | ± 0.01 | 0 |
| ARE (PL) | 281 → 202 | 2.61 fsw/h (O) | 67 h | 4 | 0.42 | 1/79 h |
| | | | | | ± 0.01 | |

Key:

- (A) Shows decompression rate begun immediately after completing upward excursion to next shallower pressure 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 P_{O₂} at maximum F_{IO₂} of 19.00%.
- (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 P_{O₂} at maximum F_{IO₂} of 25.00%.
- (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 P_{O₂} at maximum F_{IO₂} of 25.00%.
- (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 fsw¹ 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:

$$\text{UEXD} = (5.04/\text{CF}) \cdot (D_2 \cdot \text{CF} + 33)^{0.75} \quad (3)$$

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-

¹Conversions 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).

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

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

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 | |

^aData summarized from Table 1 ^bFinal operational limit as determined from D₁ 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 I 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 (maximum depth of dive 1500 fsw) | STD USN | 24 | 6 | 1/5 h |
| 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 |
| 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) |

^aPo₂ 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 I 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% O₂ 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% O₂) 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% O₂ 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% O₂ (P_{O₂} = 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 P_{O₂} 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

| Depth D_1 , fsw | Upward Excursion Distances, 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 assess 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 binomial 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), Lennessy 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:

$$\text{UEXD} = K \cdot P_{\text{min}}^{0.5} \quad (5)$$

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 $P_{\text{min}} = 883$). 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 I (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:

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

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 Hem-

pleman (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 PO_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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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 the 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 IA
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 PO 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 |