# Review of excursion procedures used in commercial heliox saturation diving

Jean-Pierre Imbert[1], Lyubisa Matity[2], Jean-Yves Massimelli[3], Christian Cadieux[4], Jan Risberg[5], Philip Bryson[6]

[1] *Divetech EURL, 1543 chemin des vignasses, 06410 Biot, France*
[2] *Hyperbaric and Tissue Viability Unit, Gozo General Hospital, Victoria VCT 2520, Malta*
[3] *Centre Hospitalier Universitaire de Nice, 30, Voie Romaine, 06001 Nice, France*
[4] *CCO Ltd, 52/2 moo 3 Tambon Tarpo - Phitsanulok 65000, Thailand*
[5] *NUI, Gravdalsveien 245, 5165 Laksevag, Norway*
[6] *TAC Healthcare Group, Wellheads Industrial Estate, Aberdeen, United Kingdom*

***Corresponding author:*** *Dr Philip Bryson, TAC Healthcare Group, Wellheads Industrial Estate, Aberdeen, AB21 7GA United Kingdom*
***ORCiD:*** *0000-0002-7815-1218*
*philip.bryson@tachealthcare.com*

**Keywords**
Decompression sickness; Decompression tables; Excursion dives; Occupational diving; Oxygen

**Abstract**
(Imbert J-P, Matity L, Massimelli J-Y, Cadieux C, Risberg J, Bryson P. Review of excursion procedures used in commercial heliox saturation diving. Diving and Hyperbaric Medicine. 2026 31 March;56(1):21–40. doi: 10.28920/dhm56.1.21-40. PMID: 41875439.)
**Introduction:** This study reviews heliox saturation procedures used in offshore commercial diving and focuses on bell excursion dives. It excludes initial compression and final decompression. Our first objective was to trace the history and the reasons behind the successive changes that led to the current practice. Our second objective was to review the current practice and identify problem areas and perspectives.
**Methods:** We first present the background of excursion diving and reference key procedures from the US Navy, Comex, and international standards. We then review the procedures of 13 anonymised diving companies and compare their sources, designs, and operation parameters.
**Results:** The current excursion procedures are derived from a few original procedures (US Navy, Comex). It appears that, without relevant scientific support since the 1980s, companies have empirically adapted these procedures to their needs. Two designs prevail: excursions from storage depth and excursions from the deepest depth. Recent innovations offer 'standard' and 'extended' excursions, sliding excursion windows, as well as shallow and deep excursions. Companies participating in the study have a low risk of DCS with excursion diving. Excursions rarely produce immediate DCS symptoms but associated bubble formation could impact the final decompression. The trend is towards reduced excursion distances and explicit post-excursion intervals. Oxygen toxicity remains a general concern in saturation diving, but the $PO_2$ values used in the procedures reviewed are unlikely to cause pulmonary toxicity according to the dose models in use.
**Conclusions:** We observed a trend towards harmonisation under the pressure of international standards and through cooperation within industry association committees. We recommend scientific monitoring of saturation divers to measure the decompression stress and support further research and development. We recommend that companies document their procedural developments to record and thus keep the lessons learned.

## Introduction

Saturation diving is commonly used in commercial offshore diving.[1] We have previously reviewed the final decompression procedures for commercial helium-oxygen (heliox) saturation diving.[2] This work focuses on excursion procedures.

Our first objective is to trace the historical background and the reasons for the successive changes that led to the current practice. Our second goal is to describe and evaluate this current practice. We have contacted offshore commercial diving companies involved in saturation diving and requested that they provide their diving manuals for review. The review of these company procedures has allowed us to 1) identify their sources, 2) trace their evolution, 3) describe their current practice, 4) estimate their safety performance, and 5) identify problem areas and trends.

We have tried to provide written references in agreement with scientific standards. However, much information related to the development of commercial saturation diving procedures has not been published in the open domain. Non-referenced information in this review should be considered as the authors sharing their personal experiences.

**Background**

UNITS

We have adhered to the units commonly used in diving manuals:

- Gas partial pressures are expressed in bar (1 bar = 100 kPa).
- Gas fractions are expressed in percentages.
- While excursion distances and water depths hold the dimension of length, they are conventionally measured by pressure gauges (for instance, a pneumofathometer or 'pneumo'). For this reason, we use metres of seawater (msw) to express water depth and bell pressure (1 msw = 1.0197 kPa according to EN 13319).[3]

Our policy regarding unit conversion is:

- When a company converted original values from feet of seawater (fsw) to msw, we kept the msw values found in the company manual, regardless of the conversion factor used. Most companies use 1 fsw = 0.303 msw according to the IMCA D 022 guidance note.[4]
- For the US Navy (USN) instructions or the companies that only use fsw, we have converted fsw into msw using 1 fsw = 0.30643 msw as specified in the USN diving manual.

BELL SATURATION EXCURSION PROCEDURE

During an excursion dive, divers are deployed from the diving support vessel (DSV) to the worksite in a diving bell (Figure 1):

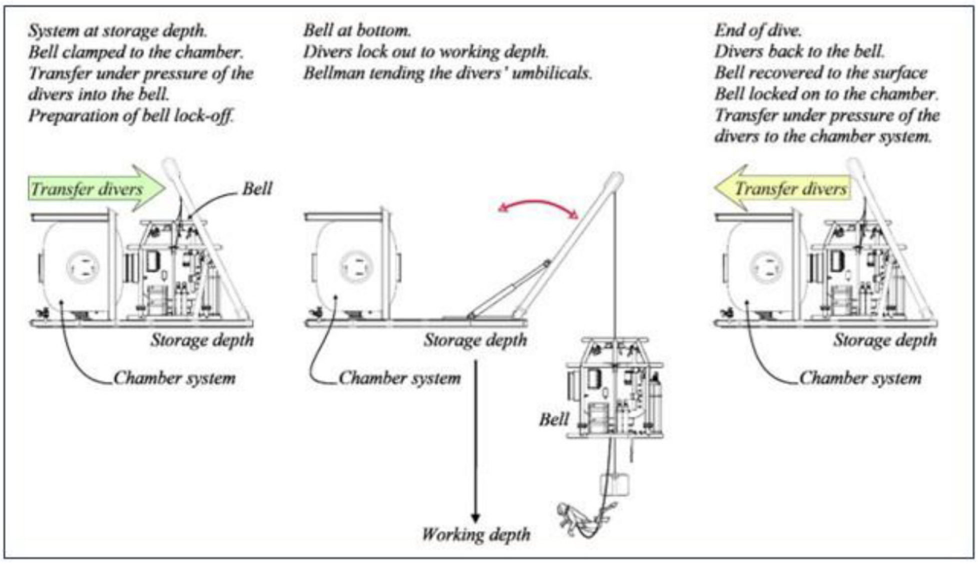
- The bell is initially locked onto the saturation chamber system. The divers are transferred under pressure (TUP) into the bell. Typically, two divers and a bellman occupy the bell.
- The bell is separated from the system (locked-off) and lowered into the sea. When the ambient hydrostatic pressure equals the bell pressure, the bottom door opens.
- The divers don their gear and lock-out for the job, with their umbilicals tended by the bellman. Divers may intermittently return to the bell to collect tools or for a rest period. At the end of their dive, the divers re-enter the bell and remove their gear.
- The bell lower door is closed and sealed by slight overpressure. The bell is then lifted to the surface.
- The bell arrives on deck and is clamped back onto the chamber system (locked-on).
- The bell is then decompressed to the chamber storage depth, and the divers are transferred under pressure back into the chamber system.

The following terms are defined in bell excursion diving:

- Ascending (or upward) excursion: an excursion shallower than the storage.
- Bell run time: the time elapsed between the lock-off and the lock-on times.
- Combined excursion: an excursion deeper and shallower than the storage depth.
- Descending (or downward) excursion: an excursion deeper than the storage depth.
- Dive time: the time spent by a diver in the water.
- Excursion: a dive or bell exposure at a pressure different from the storage depth.
- Excursion distance: the difference between the deepest and the shallowest depths reached during the excursion.
- Excursion window: the range of the excursion depths defined from the excursion distance, allowing divers to ascend and descend freely within these limits.

**Figure 1**

Illustration of the sequence of events of a bell run



- Post-excursion interval: the minimum time following an excursion before the next excursion can start.
- Pre-decompression hold time: the minimum time after the last excursion before an intermediate or final decompression can be initiated.

## HISTORY OF SATURATION EXCURSIONS

The first excursion procedures were developed for underwater habitats in the early 1960s. At that time, the concept was to consider an excursion dive as a 'bounce dive' from the habitat. Scheiner and Kelly developed a matrix of M-values from symptom-free excursions based on habitat experiments. From this matrix, they designed a set of no-decompression dives from various storage depths that could be used along with repetitive dive interval procedures.[5] During the Hydrolab project (Bahamas, 1970–1985), the first undersea research habitat used by NOAA (US National Oceanic and Atmospheric Administration), divers used excursions requiring in-water decompression stops before they could return to the storage depth (Figure 2). Hamilton also developed a model for REPEX excursions (REPetitive EXposure) based on conventional perfusion-limited gas kinetics with eight compartments with half-times ranging from five to 640 minutes. Ascent criteria were defined with traditional M-values but with a reduced slope for storage depths deeper than 70 fsw. The procedure used the number of dives in the sequence and the time interval between dives to compute a decompression penalty.[6]

Miller compiled the experience gained with air and nitrox vertical excursions from habitat projects.[7] The NOAA OPS manual, published in 1975, included Hamilton's REPEX procedures computed for air and nitrox saturation excursions.[8]

In 1969, the diving company Comex performed its first saturation operations in the Gulf of Biscayne at a depth of 100 msw. The Comex excursion procedures provided varying bottom time limitations based on varying post-dive intervals, called Ludion N/M. The term Ludion refers to an ancient toy in which a figurine ascended and descended in a water-filled glass tube. The term N/M represented the combinations of a given bottom time and the minimum post-excursion intervals. For instance, a Ludion 6/8 was associated with six hours spent at the bottom depth, followed by eight hours at the storage depth. Various combinations of Ludions (6/8, 4/12, etc.) were listed for different storage depths (Figure 3).

In 1974, the US Navy Diving Operations Handbook included saturation excursions with no-decompression limits and repetitive groups designation tables for helium-oxygen dives.[9] The 1977 revision contained excursion procedures based on unlimited durations, which became the 'Bible' for many diving companies working in the North Sea oil and gas exploration.[10]

## REFERENCE PROCEDURES

Most commercial saturation diving manuals are based on the US Navy and the Comex diving manuals. Other laboratories (Royal Navy, Institute for Environmental Medicine, Duke University, NUI) and past companies (Oceaneering, Taylor Diving) have contributed to these developments.

**Figure 2**
The dive slate of Dick Clarke, diver of Hydro-Lab, on 12 December 1974; he noted the information for an excursion dive from 42 fsw to 200 fsw for a 60 min bottom time. The slate indicates stops to be performed in water during the return to the habitat with a total decompression time of 42 min (Courtesy of Dick Clarke)

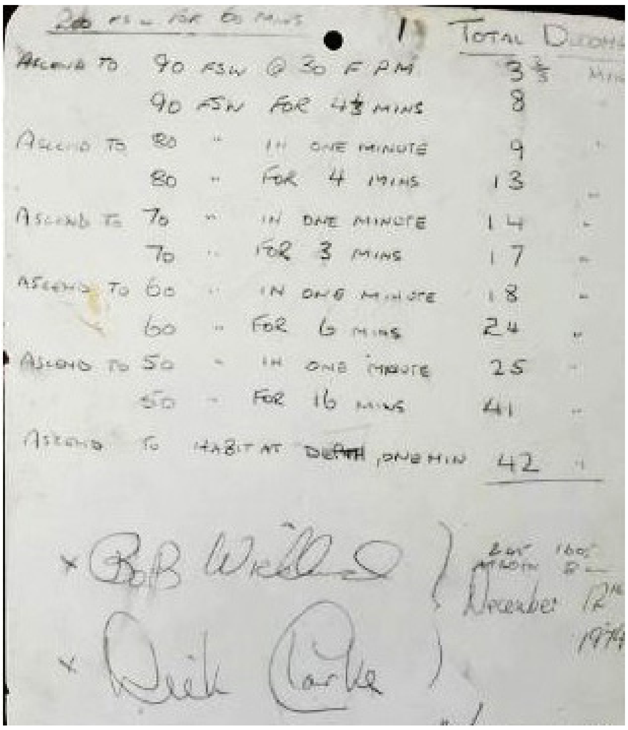
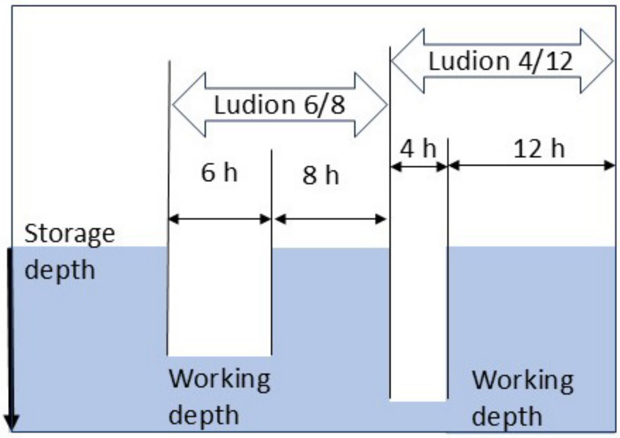



**Figure 3**
Example of 6/8 and 4/12 Comex Ludions excursions



*US Navy excursion procedures*

The USN Diving Manual has played a key role in the development of the offshore industry. It shaped minds and culture.

Bornmann computed the early US Navy helium oxygen saturation excursion tables.[11] The tables were tested by Summitt et al. at the Navy Experimental Diving Unit in 1969.[12,13] In these studies, no DCS was observed following 1,126 descending excursion dives ranging from 15 to 45 msw from storage depths ranging from 45 to 180 msw.

After the study of Barnard at the Royal Navy, the US Navy resumed its work on excursion tables.[14] The results were published after an exhaustive study of more than 240 excursion ascents ranging from 66 to 300 msw.[15] It formed the basis for the US Navy tables presented in the 1977 revision of the US Navy diving manual.[10] These tables provided unlimited-duration excursions and covered the depth range of 46 msw to 306 msw. They had significantly larger excursion distances when compared to today's commercial practices (Table 1).

The revised excursion procedures were published in the 1987 revision of the US Navy diving manual Volume 2, which included excursions defined up to the surface (Table 2). These procedures have remained unchanged since.

*Comex excursion procedures*

Comex was a leading diving company during the 1970s and 1980s. It conducted decompression research at its Marseille hyperbaric centre and used a database to monitor and validate its diving procedures until 1994.[16]

The 1986 Comex diving manual specified a fixed maximum 10 msw excursion distance, applicable to both downward and upward excursions, within a 40 to 300 msw storage depth range, with an eight-hour minimum post-excursion interval. To enhance operational flexibility, this manual also included Ludion excursions. They provided downward excursions, limited to 30 msw distance, and based on the same eight-hour post-excursion minimum interval (Table 3).

The 1994 Comex diving manual introduced standard and extended excursions (Table 4). Company evolutions, such as Stolt Comex Seaway and Acergy inherited Comex excursion procedures.

INTERNATIONAL STANDARDS AND REGULATIONS

Three countries, France, Norway, and Brazil, have regulated saturation diving with detailed specifications for ascent rates, hold times, chamber $PO_2$, etc.

*French saturation procedures*

The 1992 revision of the French diving regulations was associated with the publication of official air tables and saturation procedures known as 'MT92'.[17] These procedures are the same as those presented in the 1994 version of the Comex diving manual. The French diving regulations were revised in 2019, but the saturation procedures remained unchanged.[18] They have been used since in France and West Africa.

*Norwegian saturation procedures*

In 1984, the Norwegian Petroleum Directorate (NPD) contracted Dr Hempleman from the British Royal Navy

**Table 1**
Limits for descending excursions published in the 1977 US Navy diving manual; msw – metres of seawater

| Storage depth (msw) | Excursion distance (msw) | Descending excursion depth (msw) |
|---|---|---|
| 46 | 23 | 69 |
| 60 | 25 | 85 |
| 90 | 30 | 120 |
| 120 | 35 | 155 |
| 150 | 39 | 189 |
| 180 | 44 | 224 |
| 210 | 49 | 259 |
| 240 | 53 | 293 |

**Table 2**
Limits for descending excursions from a given storage depth published in the 2016 US Navy diving manual rev 7; msw – metres of seawater

| Storage depth (msw) | Excursion distance (msw) | Descending excursion depth (msw) |
|---|---|---|
| 15 | 14.1 | 29.1 |
| 30 | 17.8 | 47.8 |
| 45 | 20.5 | 65.5 |
| 60 | 23.3 | 83.3 |
| 90 | 27.9 | 117.9 |
| 120 | 31.6 | 151.6 |
| 150 | 35.2 | 185.2 |
| 180 | 38.6 | 218.6 |
| 210 | 41.4 | 251.4 |
| 240 | 44.1 | 284.1 |

**Table 3**

Comex 1986 Ludion N/M excursions; the excursions were only permitted deeper than 40 msw and limited to downward excursions. The minimum post-excursion interval was 8 hours; msw – metres of seawater

| Storage depth (msw) | Maximum downward excursion depth (msw) | | | |
|---|---|---|---|---|
| | Maximum bottom time / minimum interval (hours) | | | |
| | 2/8 | 4/8 | 6/8 | 8/8 |
| 45 | 70 | 63 | 60 | 58 |
| 60 | 87 | 79 | 75 | 74 |
| 90 | 120 | 110 | 106 | 105 |
| 120 | 150 | 142 | 138 | 136 |
| 150 | 180 | 174 | 169 | 167 |
| 180 | 210 | 207 | 202 | 200 |

**Table 4**

Comex 1994 standard and extended descending excursion limits from a given storage depth; the excursions are compared to those of the 2016 US Navy diving manual and expressed as fractions of the US Navy allowance; msw – metres of seawater; / – not defined

| Storage depth (msw) | Comex standard excursions | | | Comex extended excursions | | |
|---|---|---|---|---|---|---|
| | Excursion distance (msw) | Excursion depth (msw) | % of US Navy 2016 | Excursion distance (msw) | Excursion depth (msw) | % of US Navy 2016 |
| 15 | 6 | 21 | 43 | / | / | / |
| 30 | 7 | 37 | 39 | 12 | 42 | 67 |
| 45 | 8 | 53 | 39 | 16 | 61 | 78 |
| 60 | 9 | 69 | 39 | 18 | 78 | 77 |
| 90 | 10 | 100 | 36 | 20 | 110 | 72 |
| 120 | 12 | 132 | 38 | 24 | 144 | 76 |
| 150 | 13 | 163 | 37 | 26 | 176 | 74 |
| 180 | 15 | 195 | 39 | 30 | 210 | 78 |

to evaluate the saturation procedures and organise an international conference.[19] The NPD then initiated a series of meetings with participants representing the diving contractors, unions, and employer representatives to agree on the environmental threshold/dive parameters for saturation diving. After assessing the practice of five diving contractors operating in the Norwegian sector, the participants proposed a common framework based on the most conservative features.[20] The excursion procedures appear similar to those outlined in the 1994 Comex standard excursions.

The work was published in an NPD report and referenced in the first edition of the Norsok U-100 standards for manned underwater interventions in 1999. Ascending and descending excursions were based on storage depths (Table 5). These limits have not been revised since and have remained in the 2023 revisions.[21]

Risberg and Segadal recently published a report on compression and excursion procedures in saturation diving, comparing NORSOK U-100:2023 to selected international reference procedures and a limited number of commercial procedures.[22] They concluded that empirical or experimental data could not support the narrow excursion distances that allowed for shallow saturation diving.

*Brazilian saturation procedures*

When deep operations began in the Campos field in the 1980s, Comex, which had completed two deep development contracts in Bergen (Statoil 3DP and Norsk Hydro Oseberg), brought along its Norwegian expertise and became highly influential.[23]

The first national diving legislation was published in 1988. It closely aligned with North Sea standards and was based on the 1994 Comex deep saturation procedures. The Brazilian Navy then built a hyperbaric centre and validated the procedures through a series of onshore dives before they were first published in 1999 (Table 6). Brazilian diving regulations (‘Normam-15’) are now available as Rev. 2, 2016.[24] Grounded in three decades of Brazilian deep diving experience, they have become an international reference.[25,26]

**Table 5**
Sample of the Norsok U100 2023 clause 13.4.2.4 listing maximum excursion distances from storage depth; msw – metres of seawater

| Storage depth (msw) | Ascending distance (msw) | Descending distance (msw) |
|---|---|---|
| 40 to 59 | 8 | 8 |
| 60 to 79 | 9 | 9 |
| 80 to 99 | 10 | 10 |
| 100 to 119 | 11 | 11 |
| 120 to 139 | 12 | 12 |
| 140 to 180 | 13 | 13 |

**Table 6**
Normam-15 2016 standard and extended excursion distances; the excursions are compared to those of the 2016 US Navy diving manual and expressed as fractions of the US Navy allowance; msw – metres of seawater; / – not defined

| Storage depth (msw) | Brazil 2016 standard excursions | | | Brazil 2016 extended excursions | | |
|---|---|---|---|---|---|---|
| | Excursion distance (msw) | Excursion depth (msw) | % of US Navy 2016 | Excursion distance (msw) | Excursion depth (msw) | % of US Navy 2016 |
| 15 | 3 | 21 | 21 | / | / | / |
| 30 | 6 | 36 | 34 | 15 | 45 | 84 |
| 45 | 8 | 53 | 39 | 16 | 61 | 78 |
| 60 | 9 | 69 | 39 | 18 | 78 | 77 |
| 90 | 10 | 100 | 36 | 20 | 110 | 72 |
| 120 | 12 | 132 | 38 | 24 | 144 | 76 |
| 150 | 13 | 163 | 37 | 26 | 176 | 74 |
| 180 | 15 | 195 | 39 | 30 | 210 | 78 |

## DESIGN

In addition to the constraints aiming at controlling the intrinsic DCS risk, we have identified five design concepts that influences how instructions are used.

*Design 1: Ludion excursions*

The first excursions were computed with knowledge of the 70s, which referred to Haldanian algorithms.[27] The concept was to consider excursions as a no-stop, repetitive bounce diving from the storage depth. According to these models, varying distances and bottom times required varying post-excursion intervals. This was the principle of the Ludion excursions of the 1986 Comex diving manual.

*Design 2: Excursion distances defined from the deepest depth*

The US Navy simplified the procedures by considering unlimited-duration excursions that assume saturation at excursion depth. The distance of the next excursion depends on the deepest depth previously reached by the divers, which the US Navy defined as the last 48 hours. This deepest depth becomes the entry point of the excursion table and sets the ascending excursion depth independently of the storage depth. This principle was first presented in the 1977 US Navy diving manual.

*Design 3: Excursion distances defined from storage depth*

The deepest depth concept was adapted to make it possible to define excursion directly from storage depth.

In 1986, Comex drastically reduced the excursion distances to authorise the definition of the deepest depth over the last eight hours. Since divers only perform one bell dive a day and stay at storage depth for the rest of the time, the storage depth becomes the deepest depth in all cases.

The storage depth replaced the deepest as the entry point of the excursion tables, from which the limits for descending or ascending excursion depths are listed. The Norwegian Norsok U-100 procedures are a typical example of this presentation (Figure 4).

**Figure 4**
Principle of downward and upward excursions defined from the storage depth

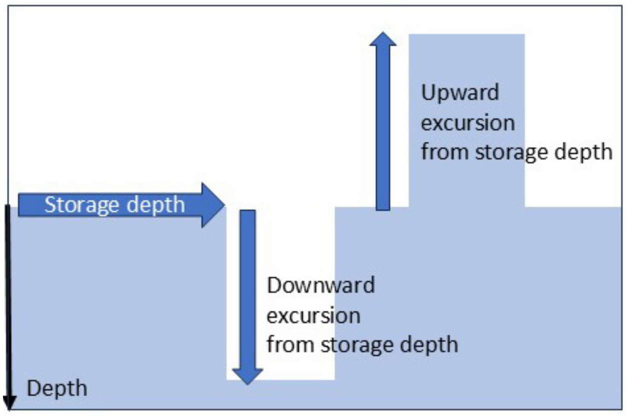



**Figure 5**
Principle of standard and extended excursions defined from storage depth

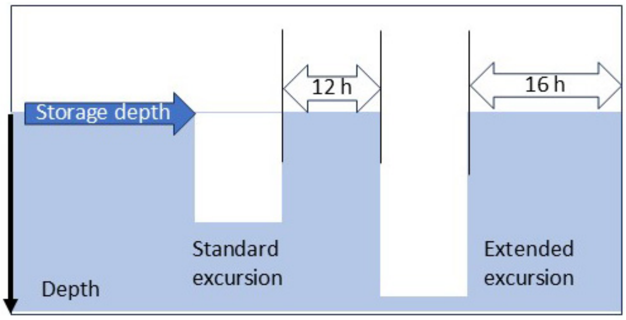
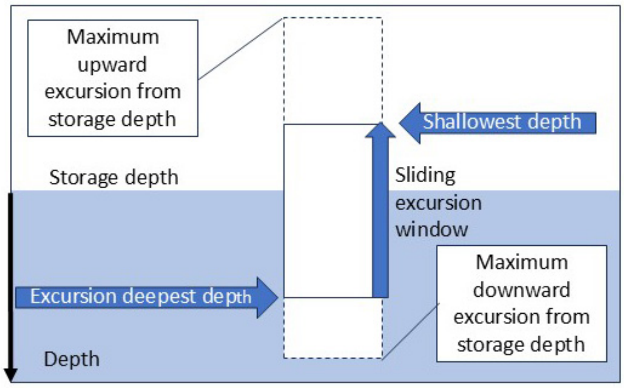



**Figure 6**
Design concept of excursions derived from the diver's deepest depth, showing the sliding excursion window




*Design 4: Standard and extended excursion distances*

The 1980s marked the development of inspection, maintenance, and repair jobs in the North Sea. Inspection work requires divers to move up and down the platform bracings, and the offshore construction managers discussed the possibility of using higher excursion windows for these specific projects. Comex revisited the concept of the Ludion N/M excursions and replaced them with standard and extended excursions (Figure 5):

- Standard excursions have moderate amplitudes (around 40% of the 1977 US Navy excursions). They can be used without restrictions for routine operations, based on a standard 12-hour post-excursion interval.
- Extended excursions provide higher amplitudes (around 75% of the 1977 US Navy excursion distance). They are only allowed for downward excursions and require a longer post-dive interval (16 h) to mitigate an increased DCS risk.

Standard and extended excursions were first used as special instructions onboard selected DSVs. Their safety performances were monitored using the Comex database.[28] As no DCS incidents were recorded after three years of evaluation, they were considered validated and finally accepted based on their measured safety track records. The Comex manual revision 1994 proposed standard and extended excursions as options for excursions from storage depth. The Brazilian Normam 15 procedures, derived from these procedures, provide a typical example of standard and extended excursions.

*Design 5: Sliding excursion window*

In the late 1990s, a new generation of large DSVs came to the North Sea. These expensive and efficient DSVs can operate on the spot market and move from one project to another. The divers had to change the storage depth accordingly. The diving companies requested flexible excursion limits to save on intermediate storage depth changes.

The idea was to change the table entry to the excursion deepest depth. Keeping the experience gained with standard and extended excursions, this allows the excursion window to slide between the downward and the upward limits of excursions from storage depth (Figure 6). The principle can be applied to both standard and extended excursions (Table 7) and allow the divers to work above and below the storage depth during the same bell dive.

COMPUTATION

*The linear model*

For the purpose of discussion, we have derived a simple equation to compute excursion distances based on Workmann's M-Value.[27] Considering a diver at pressure $P_1$,

**Table 7**
Sample of sliding excursion distances for standard and extended excursions; msw – metres of seawater

| Deepest depth (msw) | Standard excursions | | Extended excursions | |
|---|---|---|---|---|
| | Excursion distance (msw) | Shallowest depth (msw) | Excursion distance (msw) | Shallowest depth (msw) |
| 125 | 16 | 109 | 22 | 103 |
| 126 | 17 | 109 | 23 | 103 |
| 127 | 17 | 110 | 23 | 104 |
| 128 | 17 | 111 | 23 | 105 |

we seek the minimum pressure $P_2$ that the diver can reach from this initial pressure. Assuming that:

- The diver is saturated at his initial pressure.
- One compartment is involved.
- The helium and oxygen gas tensions are equal to the inhaled gas partial pressures ($P_{He}$ $PO_2$), thus ignoring the other metabolic gases and the effect of the oxygen window.[29]

We have:

E 1 $P_1 = P_{He} + P_{O2}$

Using a safe ascent condition similar to an M-Value, defined with coefficients A and B, it yields:

E 2 $P_{He} = A * P_2 + B$

Combining E 1 and E 2 gives:

E 3 $P_1 = A * P_2 + B + P_{02}$

This allows expressing the upward excursion distance (ΔP) as a linear function of P1:

E 4 $\Delta P = P_1 - P_2 = \left(1 - \frac{1}{A}\right)P_1 + \frac{(B+P_{O2})}{A}$

*Asymmetry of ascending and descending excursions*

According to Equation E4, the computation of excursion distances from a given storage depth gives different results for an upward or a downward excursion. The explanation for this asymmetry is that:

- The $P_1$ values are different. One corresponds to the excursion depth in a downward excursion, and the other to the storage depth in an upward excursion.
- The inhaled $PO_2$ are different. For a downward excursion, the starting $PO_2$ corresponds to the diving mix (0.60 to 0.80 bar). For an upward excursion, the starting $PO_2$ corresponds to the chamber atmosphere (0.40 to 0.45 bar).
- An upward excursion follows a full saturation excursion (divers have spent enough time to be saturated at the storage depth), when a downward excursion only lasts for 8 hours.

Asymmetrical excursions are presented in the US Navy 2016 manual. From a storage depth of 400 fsw (122.4 msw), the upward distance is 93 fsw (28.4 msw) and the downward distance is 105 fsw (32.1 msw).

Symmetrical excursion distances are sometimes proposed to simplify operations. The Norsok standards provide excursions from a 120 msw storage depth with symmetrical 12 msw distances above and below the storage depth. However, these procedures are known to be very conservative.

*Computation of US Navy excursions*

In 1989, Thalmann published a series of excursion tests that mentioned the historical development of the US Navy excursions.[30] The first excursion distances were initially computed from a linear relation to depth, as derived in the previous paragraph and illustrated in Figure 7. These excursions can be computed using the following expression, where UEXD is the upward excursion distance and $D_1$ is the deepest depth, defined over the range of excursions.

E 5 $UEXD = 0.136\, D_1 + 13.8$ in msw

However, the extrapolation to greater depth proved to be hazardous. In 1976, during the Comex Janus IV onshore experiment, divers performed excursion dives from a 400 msw storage depth to 430, 445, 460, and 480 msw working depths. An excursion to 480 msw corresponded to the extrapolated US Navy excursion from 400 msw. One diver presented severe inner ear symptoms after his second excursion to 460 msw.

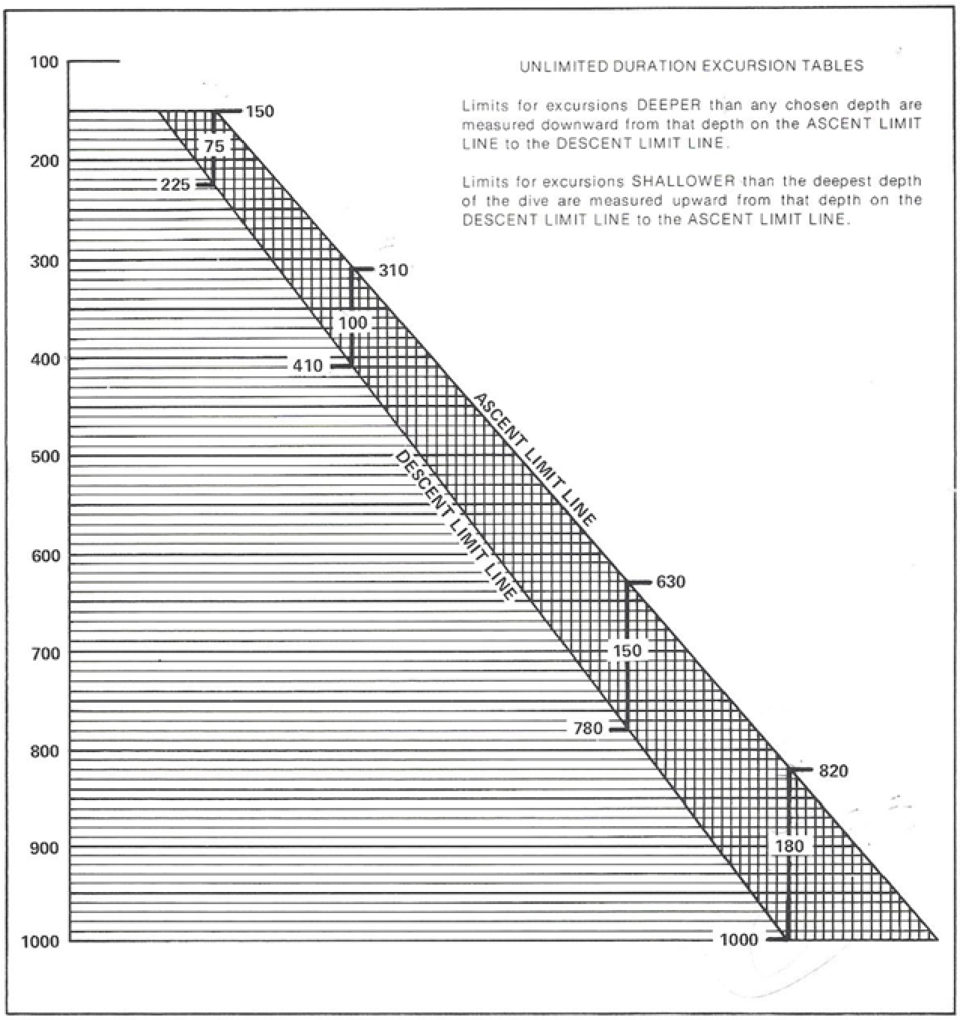
Thalmann reported that the excursions were later derived from an empirical equation proposed by Behnke in which the excursion distance is proportional to the square root of the absolute ambient pressure:[31] Thalmann further proposed the following formula (where, again, where UEXD is the upward excursion distance) that he used to generate the upward excursion published in the 1987 and 2016 US Navy diving manual revisions.[32]

E 6 $UEXD = 0.5\sqrt{(101.6\, D_1 + 3998)} - 12.7$ in fsw

*Computation of Comex excursions*

The 1994 Comex diving manual revision presented standard and extended excursions from storage depth, which were

**Figure 7**
Diagram 14-5 as per 1977 US Navy Diving Manual, which illustrates the linear algorithm used to calculate the first version of their unlimited-duration excursions in fsw




computed using two linear expressions defined from 15 to 200 msw. The expressions for upward excursions are:

E 7 *Standard excursions:* $UEXD = 0.050\,D_1 + 6\,\text{in msw}$

E 8 *Extended excursions:* $UEXD = 0.100\,D_1 + 12\,\text{in msw}$

## Methods

We have contacted 15 leading international companies and invited them to participate in the study. The conditions for participation were defined in a memorandum of understanding, signed by the authors and each diving company representative, stating that:

- The procedures could be used scientifically without revealing the company name.
- The company could review the paper before submission and retain the right to withdraw from the publication.

A total of 13 diving companies accepted to participate in the study, which are presented below in alphabetical order along with review dates for their procedure manual:

- Boskalis, Aberdeen, UK, manual rev 2024.
- DCN Diving, The Netherlands, manual rev. 2024.
- DOF Subsea, Perth, WA, manual rev. 2022-6.05.
- Helix Well Ops, Aberdeen, UK, manual rev. 2024.
- K Subsea, Singapore, manual rev. 2021.
- McDermott, Houston, Texas, USA, manual rev. 2024
- Mermaid Subsea Services, Bangkok, Thailand, manual rev. 2024.
- NDE Offshore, Dubai, manual rev. 2023.
- POSH Subsea, Singapore, manual rev. 2024.
- RockSalt Subsea, UK, manual rev. 2022.
- Shelf Subsea, Perth, WA, manual rev. 2023.
- Subsea7, Aberdeen, UK, manual rev. 2024.
- TechnipFMC, Aberdeen, UK, manual rev. 2024.

The companies have been de-identified and randomly mentioned as company A, company B, etc., and their associated excursion procedures are designated as procedure

A, procedure B, etc. These company procedures have been compared to US Navy 2016, Comex 1994, France MT92, Brazil 2016, and Norsok 2023 saturation procedures, considered references. It should be noted that the authors only reviewed the diving manuals provided. Some information they considered missing or not documented could be elsewhere in the company documentation.

## Results

The extraction of relevant data from US Navy 2016, Comex 1994, France MT92, Brazil 2016, and Norsok 2023 saturation procedures, and participating company manuals are presented in Tables 8–12.

## Discussion

### DCS INCIDENCE

Van Liew and Flynn stated that vertical excursions are associated with a threshold for clinical DCS, and this threshold depends on depth.[33] Companies do not share this information, and we did not request it from those participating in the study. It is thus difficult to evaluate the incidence of DCS associated with modern saturation excursion dives. What is known from various sources is presented below.

#### *Comex database*

Comex diving operations were recorded in the Comex database from 1977 to 1994.[16] Two DCS cases were reported immediately after returning from an excursion dive using the early versions of the Comex procedures (Table 13). At that time, the company averaged 1,000 men x saturation per year, corresponding to approximately 20,000 bell dives. The Comex database contained only two cases of DCS reported immediately after the bell excursion dive, presenting with typical inner ear symptoms. The database also established an overall incidence of DCS reported during or after final decompressions of 0.54% over the same period. They are all related to pain-only symptoms.[2, 34] It is difficult to evaluate the impact of excursion dives on the final decompression, but acute DCS symptoms presenting immediately after an excursion are rare.

#### *Seaway Hades database*

Seaway developed the Hades database to monitor their diving operations.[35] In 1978, the results published for saturation decompressions indicated an overall DCS incidence of 0.83% (2,662 exposures, 22 DCS). All cases presented as articular pain in the last part of the decompression. The publication of the Hades database did not document any DCS cases presented after an excursion dive.

#### *Norwegian Ocean Industry database*

The only diving database covering offshore commercial diving is maintained by Havtil (Norwegian Ocean Industry Authority), previously PSA (Norwegian Petroleum Safety Authority). This organisation has been collecting and publishing safety records since 1990.[36] The cases are all recorded in the Norwegian sector and, therefore, associated with diving procedures that comply with Norsok standards. The latest DCS reports in saturation diving were filed in 1993 and 2002. No case was identified as being directly related to an excursion dive.

#### *North Sea incidents in the 1990s*

During the 1990s, several DCS cases occurred in the North Sea following excursions compliant with US Navy procedures. The authors are aware of four of these cases (Table 14). Unfortunately, we have no further details about these incidents, such as the history of previous excursions, intervals, or other relevant information.

Due to these and possibly other incidents, the diving supervisors of some DSVs set rules to restrict excursions to a fraction of the maximum permitted US Navy distances. These rules were later implemented in diving manuals of North Sea companies as policies for selection of excursion distances (Table 15). These precautions have played an important role in reducing the DCS risk, as we have remained unaware of any similar incidents since.

#### *Decompression stress*

Today, DCS has become a rare event in saturation diving, and the incidence of DCS is no longer a relevant endpoint.[2] The concern has shifted to a broader approach based on the decompression stress mentioned by Brubakk et al.[37] This stress includes the effects of bubbles but also the cumulative effect of the oxidative stress associated with diving and decompression.[38] Saturation divers may perceive this decompression stress as 'decompression fatigue,' Diagnosing DCS remains difficult, potentially leading to underreporting in the commercial diving industry. The decompression stress related to saturation diving and its subsequent physiological effects can only be evaluated through comprehensive monitoring of the diver, both clinically and with non-invasive para-clinical methods.[39] Our experience is that divers' monitoring, which is part of the Undersea and Hyperbaric Medical Society recommendations, brings valuable support to the evolution of procedures.[40, 41]

### VENOUS GAS EMBOLI

VGE are commonly observed after asymptomatic dives using ultrasound Doppler or cardiac imaging. Although VGE are not predictive of DCS for a given diver, there is a positive association between the occurrence of VGE and the incidence of DCS.[42]

**Table 8**
Excursion procedures design, options, and recommended use; msw – metres of seawater

| Procedures | Source | Design concept | Working depth range (msw) | Allowance or extended excursions | Limitations of deep excursions |
|---|---|---|---|---|---|
| US Navy 2016 | | Deepest depth | 0–306 | No | No |
| Comex 1994 | | Storage depth | 10–210 | Yes | N/A |
| France MT92 | Comex | Storage depth | 9–210 | Yes | N/A |
| Brazil 2016 | Comex | Storage depth | 14–350 | N/A | No |
| Norsok 2023 | | Storage depth | 14–180 | No | N/A |
| Company A | Comex | Sliding window | 14–200 | Yes | N/A |
| Company B | US Navy | Deepest depth | 0–305 | N/A | N/A |
| Company C | Comex | Storage depth | 15–300 | Yes | Yes |
| Company D | US Navy | Deepest depth | 12–305 | No | No |
| Company E | US Navy | Deepest depth | 18–305 | No | No |
| Company F | Comex | Sliding window | 10–350 | Yes | Yes |
| Company G | US Navy | Deepest depth | 14–300 | No | No |
| Company H | US Navy | Storage depth | 10–305 | No | No |
| Company I | US Navy | Storage depth | 14–300 | Yes | No |
| Company J | US Navy | Storage depth | 0–305 | No | No |
| Company K | US Navy | Storage depth | 0–306 | No | No |
| Company L | Comex/US | Storage depth | 8–200 | Yes | N/A |
| Company M | US Navy | Deepest depth | 14–306 | No | No |

**Table 9**
Excursion operational characteristics; (1) – diving mix defined as $PO_2$ 0.60-0.80 bar for extended excursions; (2) – $PO_2$ 0.9 bar accepted in exceptional situations; (3) – chamber $PO_2$ controlled between 360 and 400 mbar when deeper than 180 msw; / – not defined; min – minute; msw – metres of seawater

| Procedures | Storage $PO_2$ (bar) | Diving mix $PO_2$ (bar) | Divers max ascent rate ($msw \cdot min^{-1}$) | Bell decomp rate ($msw \cdot min^{-1}$) |
|---|---|---|---|---|
| US Navy 2016 | 0.44–0.48 | 0.44–1.25 | 18 | 18 |
| Comex 1994 | 0.40–0.42 | 0.50–0.80 | 15 | 10 |
| France MT92 | / | / | / | / |
| Brazil 2016 | / | / | 10 | / |
| Norsok 2023 | 0.40–0.50 | / | 10 | / |
| Company A | 0.40–0.44 | 0.60–0.80 | 10 | 10 |
| Company B | 0.35–0.50 | 0.60–0.80 | 20 | 20 |
| Company C | 0.38–0.42 | 0.60–0.70 (1) | 10 | 10 |
| Company D | 0.37–0.43 | 0.60–0.80 | 10 | 5 |
| Company E | 0.38–0.42 | 0.70–0.8 (2) | 18 | 18 |
| Company F | 0.38–0.42 (3) | 0.60–0.80 | 10 | 10 |
| Company G | 0.38–0.42 | 0.70–0.90 | 18 | 18 |
| Company H | 0.44–0.48 | 0.60–0.90 | 18 | 18 |
| Company I | 0.40–0.45 | 0.60–0.80 | 18 | 18 |
| Company J | 0.35–0.45 | 0.50–0.80 | 9 | 9 |
| Company K | 0.37–0.43 | 0.60–0.90 | 18 | 18 |
| Company L | 0.40–0.42 | 0.50–0.90 | 9 | 12 |
| Company M | 0.38–0.42 | 0.60–0.90 | 10 | 10 |

**Table 10**

Post-excursion minimum time intervals; (1) – 12 h after an extended excursion before a standard excursion, 24 h between two extended excursions; (2) – 0 h after a standard excursion, 12 h after an extended excursion; (3) – 15 h after a maximum descending excursion of a standard ascending excursion, 24 h after a maximum ascending excursion; (4) – 4 h when shallower than 80 msw storage depth, 8 h when deeper; (5) – 6 h for a final decompression, 2 h for an intermediate decompression; / – not defined; min – minute; msw – metres of seawater; N/A – not applicable

| Procedures | Excursion post-interval (hours) | Standard excursion post-interval (hours) | Extended excursion post-interval (hours) | Deep excursion post-interval (hours) | Pre-decompression hold (hours) |
|---|---|---|---|---|---|
| US Navy 2016 | 48 | N/A | N/A | N/A | 0 |
| Comex 1994 | / | 0 | 12–24 h (1) | N/A | 0–12 (2) |
| France MT92 | N/A | 0 | 12 | N/A | 0 or 12 |
| Brazil 2016 | / | 12 | 48 | / | / |
| Norsok 2023 | N/A | N/A | N/A | N/A | 8 |
| Company A | N/A | 12 | 16 | / | 8 |
| Company B | 12 | / | / | / | 8 |
| Company C | N/A | 12 | 16 | 12 | 8 |
| Company D | / | / | / | / | 6 |
| Company E | / | / | / | / | 8 |
| Company F | N/A | 12 | 16 | 12 | 8 |
| Company G | / | / | / | / | 6 |
| Company H | / | / | / | / | 6–2 (5) |
| Company I | N/A | 12 | 12 | / | 8 |
| Company J | / | / | / | / | / |
| Company K | / | / | / | / | 4 to 8 (4) |
| Company L | N/A | 12 | 15–24 (3) | / | 8 |
| Company M | / | / | / | / | 8 |

**Table 11**

The permitted standard descending excursion distance (msw) for typical storage depths for companies using standard and extended excursion tables; / – not defined; msw – metres of seawater

| Organisation | Storage depth (msw) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
| US Navy 2016 | 14 | 18 | 24 | 28 | 32 | 35 | 39 | 42 | 44 |
| Comex 1994 | 6 | 7 | 9 | 10 | 12 | 13 | 15 | / | / |
| France MT92 | 6 | 7 | 9 | 10 | 12 | 13 | 15 | / | / |
| Brazil 2016 | 3 | 6 | 9 | 10 | 12 | 13 | 15 | 15 | 15 |
| Norsok 2023 | 1 | 6 | 9 | 10 | 12 | 13 | 13 | / | / |
| Company A | 6 | 9 | 12 | 15 | 18 | 20 | 20 | / | / |
| Company C | / | 8 | 10 | 13 | 15 | 18 | 20 | 15 | 15 |
| Company F | 6 | 9 | 12 | 15 | 18 | 20 | 20 | 15 | 15 |
| Company I | / | 14 | 18 | 21 | 24 | 27 | 29 | 31 | 33 |
| Company L | 3 | 6 | 8 | 13 | 15 | 17 | / | / | / |

Arterial and venous bubbles were observed in the six divers following ascending excursions from 300 msw to 250 msw during the NUI Deep Ex I experimental dive.[43,44] It must be noted that these detections were related to deep excursions largely exceeding the distances presently used in commercial diving. We recently reported findings from a study of commercial divers in the North Sea Danish sector, monitoring subclavian VGE one hour after descending excursions from 37 to 45 msw. No bubbles were detected.[39]

Based in large part on the strong association between inner ear DCS and patent foramen ovale (PFO), Doolette and Mitchell proposed a model of inner ear DCS based on shunted arterial bubbles reaching the inner at the time the

**Table 12**
The maximum permitted descending excursion distance (msw) for typical storage depths, for companies using extended or maximum excursion tables; companies using US Navy excursion procedures are listed as using maximum excursions. / – not defined; msw – metres of seawater

| Organisation | Storage depth (msw) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 |
| US Navy 2016 | 14 | 18 | 24 | 28 | 32 | 35 | 39 | 41 | 44 |
| Comex 1994 | / | 15 | 18 | 21 | 24 | 27 | 30 | / | / |
| France MT92 | / | 15 | 18 | 21 | 24 | 27 | 30 | / | / |
| Brazil 2016 | / | 15 | 18 | 20 | 24 | 26 | 30 | 30 | 30 |
| Norsok 2023 | / | / | / | / | / | / | / | / | / |
| Company A | 6 | 9 | 12 | 15 | 18 | 20 | / | / | / |
| Company B | 14 | 18 | 23 | 28 | 31 | 35 | 38 | 41 | 44 |
| Company C | / | 10 | 13 | 17 | 20 | 24 | 27 | / | / |
| Company D | / | 17 | 23 | 28 | 31 | 35 | 38 | 41 | 44 |
| Company E | / | 14 | 17 | 21 | 24 | 26 | 29 | 31 | 33 |
| Company F | 9 | 11 | 16 | 21 | 25 | 30 | / | / | / |
| Company G | 14 | 18 | 23 | 28 | 31 | 35 | 38 | 41 | 44 |
| Company H | 14 | 18 | 23 | 28 | 31 | 35 | 38 | 41 | 44 |
| Company I | / | 18 | 23 | 28 | 31 | 35 | 38 | 41 | 44 |
| Company J | / | 18 | 24 | 28 | 32 | 35 | 38 | 41 | 44 |
| Company K | 14 | 17 | 23 | 28 | 31 | 35 | 38 | 41 | 44 |
| Company L | 6 | 12 | 17 | 21 | 26 | 30 | 35 | / | / |
| Company M | 0 | 18 | 24 | 28 | 32 | 35 | 39 | 41 | 44 |

**Table 13**
Decompression sickness (DCS) cases presenting immediately after returning from a bell excursion dive reported in the Comex database; msw – metres of seawater

| Year | Working depth (msw) | Distance (msw) | Storage depth (msw) | DCS |
|---|---|---|---|---|
| 1984 | 40 | 10 | 30 | Inner ear |
| 1985 | 137 | 20 | 117 | Inner ear |

**Table 14**
Decompression sickness (DCS) cases reported in the 1990s, in the North Sea, immediately after the return to storage depth from an excursion dive; msw – metres of seawater

| Year | Working depth (msw) | Storage depth (msw) | Excursion distance (msw) | DCS |
|---|---|---|---|---|
| 1992 | 146 | 126 | 20 | Inner ear |
| 1994 | 78 | 56 | 22 | Inner ear |
| 1997 | 131 | 114 | 17 | Inner ear |
| 2000 | 93 | 76 | 17 | Inner ear |

local tissues are supersaturated. They assumed that this situation causes inward gas diffusion and bubble growth.[45] In a second publication, the authors reviewed inner ear DCS cases observed during the US Navy excursion trials and various deep diving experiments.[46] They modelled the survival of microbubbles reaching the arterial side and concluded that arterial bubbles have longer survival times at higher pressures and are more likely to reach the inner ear in larger numbers and sizes. This was used to explain the differences observed in bubble measurements between deep excursions and standard commercial excursions.

The data listed in their paper indicate that VGE are detected during the excursion time in an upward excursion and during the post-excursion time in a downward excursion. It can be expected that a working diver (hyperventilation, muscular effort) is more likely to open a PFO or intrapulmonary arteriovenous anastomoses and shunt arterial microbubbles than a diver returning to storage depth for a shower and dinner. This could explain why upward excursions have a bad reputation. Companies sometimes recommend planning work with a downward excursion rather than an upward one in their diving manual. The authors admit that they have no data to support this sort of policy.

**Table 15**
Policies developed by companies referring to the US Navy excursion procedures

| Company | Recommendation for the use of US Navy excursion distances |
|---|---|
| Company B | The maximum operating excursions should not be considered as a normal operational procedure. |
| Company D | An optimum operating range (50% of the excursion table values) for maximum descending and ascending distances is preferable wherever diving operations permit. |
| Company G | Maximum upward excursions to the limit of the tables shall not be carried out except for light inspection work. |
| Company H | Upward excursions should be limited to 75% of the distance. |

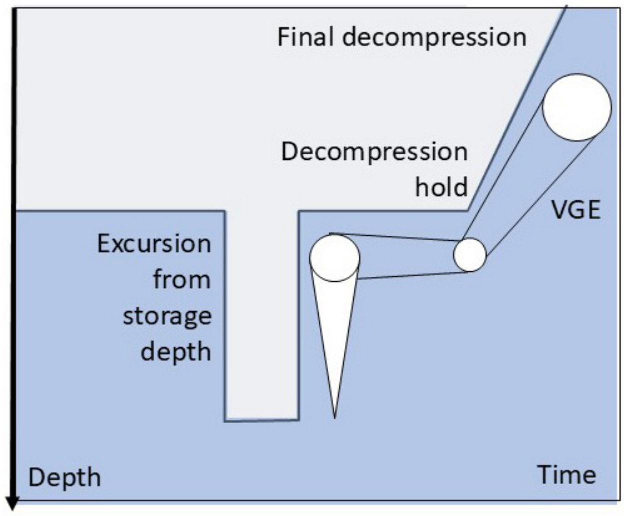
*Modelling VGE during excursion dives*

Van Liew and Burkard developed a model that Flook used to predict the volume of VGE gas produced after decompression in man.[47] This bubble growth model was calibrated using actual VGE measurements and allowed the estimation of the volume of the bubbles produced during a saturation profile.[48] The model confirmed that the duration of the post-excursion interval influences bubble growth during the following decompression, particularly after high-distance excursions. Flook concluded that the current excursion distances were unlikely to cause DCS but that combining excursions and the final decompression could generate a population of residual bubbles responsible for late DCS symptoms.

In 1989, Thalmann published the results of a series of tests that led to the revision of the US Navy excursion procedures.[30] Fifty divers performed 164 man-excursion dives during nine saturation experiments. During these tests, nine cases of joint pain occurred, which occurred eight hours or more into the saturation decompression. This seems to confirm Flook's theory, according to which bubbles remaining from the last bell excursion dive could provoke DCS symptoms during the final decompression (Figure 8).

Present commercial saturation diving procedures are not expected to cause DCS during or immediately following

**Figure 8**
Schematic illustration of Flook's theory according to which bubbles produced after an excursion could interfere with the final decompression




excursions. However, it is suspected that bubbles produced after the excursion dive could increase the DCS risk during the final decompression. The specification of a minimal post-excursion interval and pre-decompression hold is designed to mitigate this risk.

## OXYGEN TOXICITY

*Role of oxygen in excursions*

The inspired $PO_2$ sets the inert gas gradient, which in turn influences gas exchange. Although raised $PO_2$s allow larger excursion distances, high oxygen levels generate reactive oxygen species that interfere with cell functions. While central nervous system toxicity is usually not a concern in saturation diving, pulmonary toxicity (POT) can be a limiting factor.

The $PO_2$ during an excursion dive must be balanced between: A lower limit based on the physiological demand, safety, and permitted excursion distance (Equation 4).

An upper limit based on oxygen toxicity in general and POT in particular.

*Pulmonary oxygen toxicity*

Divers may experience POT if exposed to hyperoxic breathing gas for prolonged periods.[49] It is challenging to isolate the effects of hyperoxia from those caused by other mechanisms, such as immersion and high pressures, since many factors are known to affect pulmonary function after dives.[50] Most experimental studies on POT have focused on the effects of relatively short-lasting exposures to $PO_2$

exceeding 1 bar.[51] However, the effects of long-lasting exposure to low $PO_2$ ($PO_2 < 1$ bar) are less known. Thorsen et al. measured pulmonary function after a dry 28-day helium-nitrogen-oxygen saturation dive to 15 msw with a $PO_2$ of 0.4 bar in the bottom phase, followed by intermittent exposures to $PO_2 = 0.75$ bar. The $PO_2$ was 0.5 bar during the decompression phase.[52] They reported a temporary 10.6% reduction in transfer factor for carbon monoxide immediately after the dive, but a permanent 9.3% reduction in mid-expiratory flow volumes ($FEF_{25–75\%}$), persistent for three years after the dive. The low breathing gas density (1.6 $g \cdot L^{-1}$) and dry exposure suggest that hyperoxia rather than respiratory work or immersion caused the small-airway dysfunction. Suzuki reported a 4–13% decrease in pulmonary carbon monoxide diffusion capacity (DLCO) immediately after saturation dives to 300 and 320 msw lasting 14–16 days with an inspired $PO_2$ of 0.42 bar during the bottom phase and 0.5 bar during decompression.[53]

Thorsen et al. also demonstrated that cycling the inspired $PO_2$ between 0.3 and 0.5 bar during saturation decompression has a protective pulmonary effect, as no change in pulmonary function was observed following a 19-day experimental saturation dive with this decompression procedure, despite intermittent hyperoxic exposures to $PO_2 = 0.7$ bar in the bottom phase.[54]

These findings suggest that the increased constant $PO_2$ during saturation decompression, rather than the intermittent hyperoxic exposures during excursion dives, has the greatest impact on pulmonary function following saturation dives with $PO_2$ levels similar to those practiced in commercial saturation diving. From the data collected in Table 9 we would not expect the excursion $PO_2$ values used in the excursion procedures listed in this work to cause clinically relevant POT.

*Evaluation of the oxygen toxicity dose*

The divers' tolerance to pulmonary oxygen toxicity is difficult to measure and predict.[55] Because of their simplicity, the industry approach has traditionally managed exposures using the units of pulmonary toxic dose (UPTD) or oxygen toxicity unit (OTU).[56]

Recent advances suggest that divers' occupational hyperoxic exposure during surface-oriented diving is best monitored using the 'equivalent surface oxygen time' (ESOT) concept rather than the UPTD terms previously used.[57] However, the ESOT concept is not designed for saturation diving.

Arieli has proposed a hyperoxic exposure monitoring system applicable for saturation diving.[58] The model has not been validated, and the kinetics of POT development and recovery during and after saturation remain unresolved.

*Oxygen in the diving mix*

The current saturation procedures result from successive empirical adjustments that have progressively reduced the excursion distance while keeping the $PO_2$ specifications. The current oxygen specifications for the diving mix may exceed what is needed for the excursion distances.

We note that company C has restricted the diving $PO_2$ range to 0.60–0.70 bar for their standard excursions, which only authorise moderate excursion distances. Scientific work would be required to adjust the $PO_2$ levels in the current excursion procedures.

## OPERATIONAL HAZARDS

The risk for a diver during a bell excursion dive is to exceed his permitted excursion envelope. We are aware of three typical incidents:

- A diving support vessel operating two bells back-to-back (continuous presence of divers at the bottom). A diver from the second bell locked out, and his umbilical was caught by the first bell when it started its ascent. The diver was pulled off his limits until the first bell ascent was finally stopped.
- A combined divers and ROV operations at shallow depths. The ROV caught the diver's umbilical in its tether and lifted him outside his excursion limits by a few metres.
- Divers lifted off the seabed by clump weight. Divers were at work at 42 msw with storage depth at 34 msw. The taut wire winch was activated to recover the system from the seabed and caught the divers' umbilicals. Divers were lifted to 13 msw (29 msw upward distance). No signs or symptoms were reported, but divers were given five cycles of therapeutic gas and rehydrated as a precaution.

The potential consequences of these degraded conditions must be evaluated on a case-by-case basis. Divers may not present immediate and detectable DCS symptoms. The contingency procedure is generally to abort the bell run and keep the diver under observation. Severe violations of the excursion limits may require additional hyperbaric oxygen breathing. In such situations, the 1977 US Navy excursion limits provide practical guidelines because they indicate 'what has been done before,' which helps 'calibrate' the situation.

## TRENDS

We have observed discrepancies between procedures, primarily due to their historical development. However, as discussed during the DMAC 2014 meeting in Aberdeen, we do have sufficient data today to conclude the consequences of these differences on the divers' health.[59] We also observe the harmonisation of the procedures.

**Figure 9**
Plot of the excursion distance versus the excursion start depth using the standard descending excursion tables; msw – metres of seawater

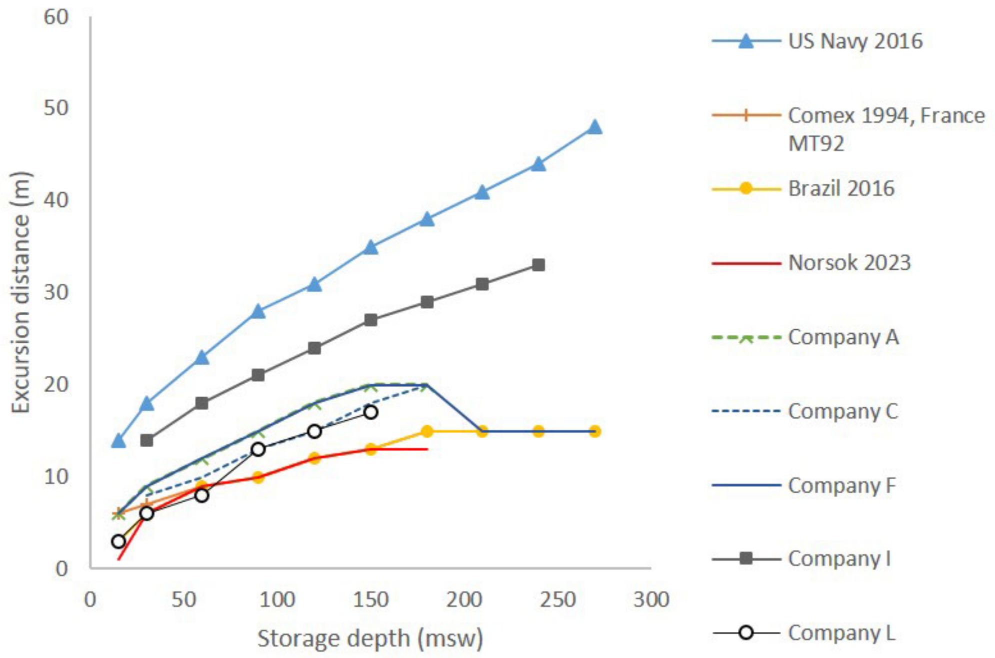
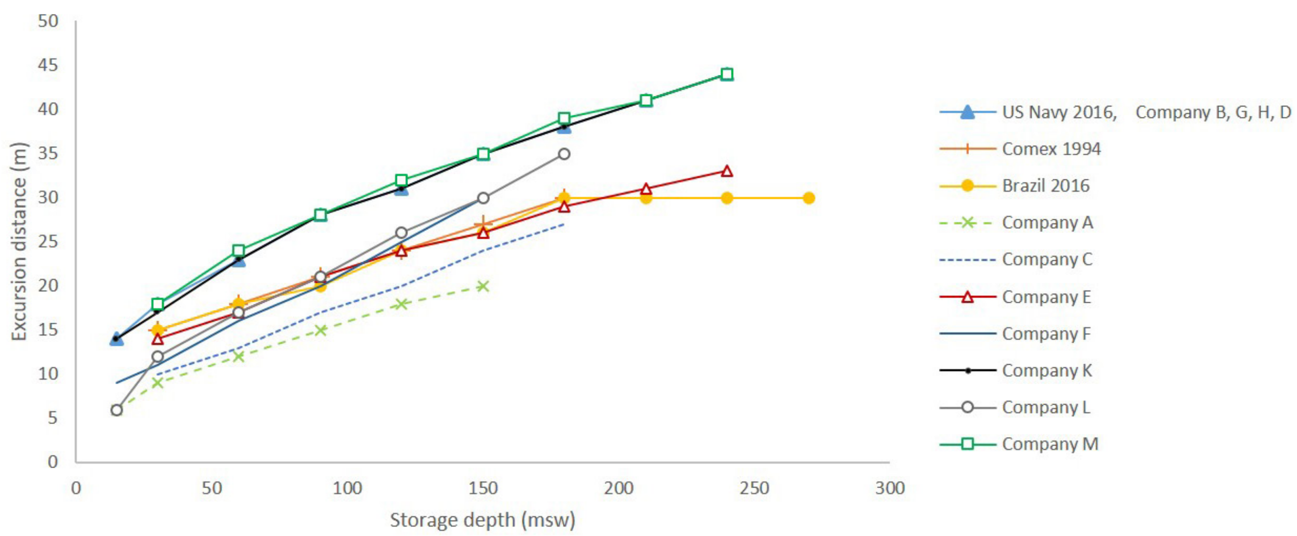



**Figure 10**
Plot of the excursion distance versus the excursion start depth using the extended or maximum descending excursion tables; msw – metres of seawater




*Reduction of excursion distances*

The US Navy excursion procedures that once ruled the offshore diving industry are now considered the upper limit of what can be done.

A consensus seems to have emerged on using moderate excursion distance (40–60% of the 1977 US Navy distances) for routine operations and keeping Extended excursion (70–75% of the 1977 US Navy distances) for exceptional situations (Figure 9 and Figure 10).

Another mitigating procedure has been the introduction of standard excursions, which further reduced the excursion distances for routine operations (Table 16).

**Table 16**
Standard excursion distances expressed as fractions of US Navy diving manual 2016

| Company | % of 2016 US Navy distances |
|---|---|
| Comex | 39–43% |
| Norsok | 37–38% |
| A | 43–57% |
| C | 44–52% |
| F | 43–57% |
| L | 21–49% |

*Extension to shallower depths*

The performance of modern diving DSVs has permitted saturation divers to operate at depths that once were the domain of air diving. The excursion procedures have been extended to shallow waters, up to 14 msw storage depth, or even shallower (Table 8). The US Navy diving manual 2016 rev. 7 proposes a direct excursion ascent from 29 fsw (8.9 msw) to the surface.

On the one hand, shallow excursions allow adapting to emerging markets, such as wind farm installations, and permit filling the planning of DSV with saturation projects. On the other hand, excursion dives from shallow storage depths are challenging to plan because of operational issues. The bell standoff frame distance or even the hull clearance limits the access. Swim lines must be installed to help the diver stay within his narrow excursion window (4 msw at 14 msw). The influence of swell and waves perturbs the operations.

The problem is to define a computational algorithm that could optimise these shallow excursions. It must be noted that saturation excursions cannot be extrapolated to hypobaric exposures or space extra-vehicular activity. It can be assumed that at low ambient pressures, Boyle's law becomes predominant and activates more complex bubble scenarios. The analysis of new experiences and the review of new theoretical models are required.

*Extension to deeper depths*

In the 1990s, Brazilian diving operations in the Campos field provided the industry with a large-scale deep-diving experience.[23] It was then observed that deeper than 200 msw, the rapid pressure change associated with excursion dives could induce high pressure neurological syndrome (HPNS) symptoms, essentially hand tremors. As a precaution, the excursion distances were reduced to 15 msw to control HPNS when diving deeper than 200 msw. This feature was later incorporated into the Brazilian diving regulations Normam-15/DPC edition.[24]

Deep diving has remained limited outside the Brazilian Campos field. However, there have been few occasions for diving deeper than 200 msw in Libya and the eastern Mediterranean over the last decade. Companies A, C, and F have designed original deep excursion procedures with reduced excursion distances to control HPNS.

*Harmonisation of the minimum post-excursion interval*

The companies have different practices regarding the post-excursion interval. Several diving manuals reviewed (Companies D, G, H, J, K, M) did not specify a minimum interval between bell excursion dives. Their operations are based on one team performing one daily excursion, which implicitly ensures a minimum 12-hour interval between dives. All the other diving manuals stipulate a minimum 12 hours post-excursion interval for a standard excursion.

For extended or maximum excursions, this post-dive interval is set to 16 hours for three companies (Companies A, C, F). Considering an eight-hour bell run time, this pattern still fits into a 24-hour cycle. Company L uses longer post-dive intervals for maximum excursion (15–24 h).

*Harmonisation of the minimum pre-decompression hold*

The Norsok standards first introduced the pre-decompression hold as a minimum time interval defined after the last excursion dive before the divers can start a final or intermediate decompression. As documented in a previous publication, this hold is now harmonised to eight hours.[2] However, one company does not specify this hold (Company J). Two others use six hours (Company G) or two hours (Company H). This last value is used as an extension to the US Navy diving manual rev. 7 rule (paragraph 13.23.3), which specifies a two-hour hold after an upward excursion at a depth shallower than 60 msw.

## Conclusions

We have reviewed the history of excursion diving and the procedures of 13 companies involved in heliox saturation diving.

The comparison of these excursion procedures shows that:

- Current saturation procedures are derived from the US Navy and the Comex procedures.
- Diving companies have since empirically modified these procedures according to their needs. This explains the differences observed in the excursion distances and presentations.
- DCS associated with bell excursion dives has become a rare event.

The review reveals that:

- Companies are moving towards reduced excursion distances for routine operations.
- Companies seek higher flexibility to manage modern DSVs. This is illustrated by the recent introduction of sliding excursion windows or shallow excursions.

We believe that saturation excursion procedures will continue to evolve. Scientific research must support this evolution. Scientific monitoring of saturation divers permits measuring the decompression stress and supporting further excursion evolution. We recommend that companies document their procedural developments to record and thus keep the lessons learned.

## References


1 Cadieux C. Description of a saturation diving system, Diving and ROV Specialist, 2021. [cited 2025 September 30]. Available from: https://diving-rov-specialists.com/index_htm_files/div-rov_description-saturation-system.pdf.
2 Imbert JP, Matity L, Massimelli JY, Bryson P. Review of saturation decompression procedures used in commercial diving. Diving Hyperb Med. 2024;54:23–38. doi: 10.28920/dhm54.1.23-38. PMID: 38507907. PMCID: PMC11065503.
3 EN 13319:2000 – Diving accessories – Depth gauges and combined depth and time measuring devices – Functional and safety requirements, test methods, European Standards, 2000. [cited 2025 Sep 30]. Available from: https://www.en-standard.eu/search/?q=EN+13319%3A2000.
4 IMCA. D 022 rev.1.3 Guidance for Diving Supervisors, The International Maritime Contractors Association, 2024. [cited 2025 Sep 30]. Available from: https://www.imca-int.com/resources/technical-library/document/1a4b165f-c55b-ee11-8def-6045bdd2c9bc/.
5 Schreiner HR, Kelley PL. Computation of decompression schedules for repetitive saturation excursion dives. Aerosp Med. 1970;41:491–4. PMID: 5430675.
6 Hamilton RW, Kenyon D, Peterson R. Repex habitat diving procedures: Repetitive vertical excursions, oxygen limits, and surfacing techniques, 1988. [cited 2025 Sep 30]. Available from: https://repository.library.noaa.gov/view/noaa/60671/noaa_60671_DS1.pdf.
7 Miller JW. Vertical excursions breathing air from nitrogen-oxygen or air saturation exposures: US Department of Commerce, National Oceanic and Atmospheric Administration. 1976. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-a_106-vertical-excursions-breathing-air-from-nitrogen-oxygen-or-air-sat%20.pdf.
8 Joiner JT. NOAA diving manual: Diving for science and technology: National Oceanic and Atmospheric Administration; 2001.
9 US Navy diving operations handbook, US Navy Department, 1974. Report: NAVSHIP 0994-009-6010. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/history-56-handbook-us-navy-diving-operations-1974.pdf.
10 US Navy diving manual, volume 2, Change 1. Mixed gas diving. NAVSEA 0994-LP-001-9010. US Department of the Navy. Washington (DC); 1977. [cited 2025 Sep 30]. Available from: https://apps.dtic.mil/sti/tr/pdf/ADA112710.pdf.
11 Bornmann RC. Helium-Oxygen saturation-excursion diving for US Navy. In: Lambertsen CJ, editor. Underwater physiology. Proceedings of the fourth symposium on underwater physiology. New York: Academic Press; 1971. p. 529–36.
12 Summitt JK, Herron JM, Flynn ET. Repetitive excursion dives from saturated depths on helium-oxygen. Phase III. Saturation depth 300 Feet, Navy Experimental Diving Unit, Report: 2-70. 1970. [cited 2025 Sep 30]. Available from: https://apps.dtic.mil/sti/citations/AD0723172.
13 Summitt JK, Alexander JM, Flynn ET, Edward T, Kuly JW. Repetitive excursion dives from saturated depths on helium-oxygen mixtures. Phase IV. Saturation depth 500 feet, saturation depth 600 feet, Navy Experimental Diving Unit, Report: 7-70. 1970. [cited 2025 Sep 30]. Available from: https://apps.dtic.mil/sti/citations/AD0723173.
14 Barnard EP. Fundamental studies in decompression from steady-state exposures. In: Lambertsen CJ, editor. Proceedings of the fifth symposium on underwater physiology. Bethesda: Federation of American Societies for Experimental Biology; 1976. p. 263–71.
15 Spaur W, Thalmann E, Flynn E, Zumrick J, Reedy T, Ringelberg J. Development of unlimited duration excursion tables and procedures for helium-oxygen saturation diving. Undersea Biomed Res. 1978;5:159–77. PMID: 675881.
16 Imbert JP, Montbarbon S. Presentation of the Comex database. In: Sterk W, Hamilton, RW, editor. EUBS workshop on operational dives and decompression data: collection and analysis, 11-18th August. Amsterdam, The Netherlands; 1990. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-b_120-presentation-comex-diving-database.pdf.
17 Ministère du Travail. Travaux en Milieu Hyperbare. Mesures particulières de prévention. Imprimerie du Journal Officiel, 26 rue Desaix, 75732 Paris cedex 15: Bulletin Officiel de la République Francaise. 1992. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/history-27-french-decree-30-october-2012.pdf.
18 Ministère du Travail. Arreté du 14 mai 2019 définissant les procédures d'accès, de séjour, de sortie et d'organisation du travail pour les interventions en milieu hyperbare, Bulletin Officiel de la République Francaise, 2019. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/docs-16-tables-mt2019.pdf.
19 Hempleman V. The safety evaluation of saturation decompression tables, Report: I82-7527-203.6. Norwegian Petroleum Directorate; 1986. [cited 2025 Sep 30]. Available from: https://www.ptil.no/contentassets/350fcc45128449329b7b92c78f6100a4/hempelman---safety-evaluation-of-saturation-decompression-tables-1986.pdf.
20 Oljedirektoratet [Norwegian Petroleum Directorate]. Rapport om sammenligning av metningsdykketabeller og utarbeidelse av rammebetingelser for standardisering [Report on comparison of saturation diving tables and preparation of frame conditions for standardization], Report: OD-91-12. 1991.
21 NORSOK. U-100 Manned underwater operations rev. 6, NORSOK, 2023. [cited 2025 Sep 30]. Available from: https://standard.no/en/sectors/petroleum/norsok-standards/u-underwater-op/u-100manned-underwater-operations/.
22 Risberg J, Segadal K. Compression and excursion parameters for saturation dives 0-250 msw, NUI AS, Report: 2023-69. Norway; 2023. [cited 2025 Sep 30]. Available from: https://www.havtil.no/contentassets/04882bf9c4054c0989f0fd70fc8c05e6/2022_1121-prosjektrapport-compression-and-excursion-parameters-for-saturation-diving.pdf.
23 Imbert JP. Deep diving: the Comex experience. In: Hope A, Risberg J, editors. Long-term health effects of diving The Godøysund 1993 consensus conference revisited; September 15-17th, Bergen, Norway: NUI AS; 2005. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-c_12-deep-diving-comex-experience-JP.pdf.

24 Normam-15 DPC. Atividades Subaquáticas, Capitulo 11 Tabelas de mergulho, rev 2, 2016. [cited 2025 Sep 30]. Available from: https://www.marinha.mil.br/dpc/normas.
25 Vivacqua R. Practical experience of the use of deep heliox tables with specific focus on medical, physical and psychological aspects – Fugro Brasil. Proceedings of the annual IMCA diving seminar and DMAC workshop; 25-26th September 2017; London, UK; 2017.
26 Cadieux C. Diving management study no 5: Implement Normam 15/DPC saturation diving procedures, 2019. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/cco-study-5-implement-normam-15-saturation-07-aug-25.pdf.
27 Workman RD. Calculation of decompression schedules for nitrogen-oxygen and helium-oxygen dives, US Navy Exp Diving Unit, Report: Res Rep 6-65. 1965. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-a_102-calculation-deco-schedules-nitrogen-oxy-and-helium-oxy.pdf.
28 Imbert JP, Bontoux M. A method for introducing new decompression procedures. Proceedings of the Undersea Medical Workshop on validation of decompression schedules; 13-14th February; Bethesda, Maryland: Undersea and Hyperbaric Medical Society; 1987. p. 13–4. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-b_94-a-method-for-introducing-new-deco.pdf.
29 Kot J, Sicko Z, Doboszynski T. The extended oxygen window concept for programming saturation decompressions using air and nitrox. PLoS One. 2015;10(6):e0130835. doi: 10.1371/journal.pone.0130835. PMID: 26111113. PMCID: PMC4482426.
30 Thalmann ED. Testing of revised unlimited-duration upward excursions during helium-oxygen saturation dives. Undersea Biomed Res. 1989;16:195–218. PMID: 2741254.
31 Behnke AR. The square-root principle in the calculation of one-stage (no-stop) decompression tables. Undersea Biomed Res. 1979;6:357–65. PMID: 538864.
32 US Navy diving manual, Revision 7. NAVSEA 0910-LP-115-1921. US Department of the Navy ed. Washington, DC, 20350. 2016. [cited 2025 Sep 30]. Available from: https://diving-rov-specialists.com/index_htm_files/docs-14-usn-manual-rev7.pdf.
33 Van Liew HD, Flynn ET. Direct ascent from air and $N_2$-$O_2$ saturation dives in humans: DCS risk and evidence of a threshold. Undersea Hyperb Med. 2005;32:409–19. PMID: 16509283.
34 Imbert JP, Bontoux M. Diving data bank: a unique tool for diving procedures development. 20th Annual offshore technology conference; May 2nd-5th Houston, Texas, USA; 1988. [cited 2025 September 30]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-b_17-diving-data-bank-a-tool-for-diving-procedrues-development.pdf.
35 Jacobsen G, Jacobsen JE, Peterson RE, McLellan JH, Brooke ST, Nome T, et al. Decompression sickness from saturation diving: a case control study of some diving exposure characteristics. Undersea Hyperb Med. 1997;24:73–80. PMID: 9171466.
36 Rapport fra ptil's dykkedataabse dsy, PSA; 2022. [cited 2025 Sep 30]. Available from: https://www.ptil.no/contentassets/7284426234ae40cdaa62e2037ed2bf35/dsys_2022-rapport.pdf.
37 Brubakk AO, Ross JA, Thom SR. Saturation diving; physiology and pathophysiology. Compr Physiol. 2014;4:1229–72. doi: 10.1002/cphy.c130048. PMID: 24944036.
38 Mrakic-Sposta S, Vezzoli A, D'Alessandro F, Paganini M, Dellanoce C, Cialoni D, et al. Change in oxidative stress biomarkers during 30 days in saturation dive: a pilot study. Int J Environ Res Public Health. 2020;17(19):7718. doi: 10.3390/ijerph17197118. PMID: 32998440. PMCID: PMC7579105.
39 Imbert JP, Barbaud A, Stevens S, Miller C, Peace H, Rossin H, et al. Evaluation of North Sea saturation procedures through divers monitoring. Int Marit Health. 2024;75:89–102. doi: 10.5603/imh.99606. PMID: 38949219.
40 Wekre SL, Landsverk HD, Lautridou J, Hjelde A, Imbert JP, Balestra C, et al. Hydration status during commercial saturation diving measured by bioimpedance and urine specific gravity. Front Physiol. 2022;13:971757. doi: 10.3389/fphys.2022.971757. PMID: 36246118. PMCID: PMC9559868.
41 Imbert JP, Balestra C, Kiboub FZ, Loennechen Ø, Eftedal I. Commercial divers' subjective evaluation of saturation. Front Psychol. 2018;9:2774. doi: 10.3389/fpsyg.2018.02774. PMID: 30692957. PMCID: PMC6340096.
42 Nishi RY, Brubakk AO, Eftedal OS. Bubble detection. In: Brubakk AO, Neumann TS, editors. Physiology and medicine of diving. 5th ed. London, UK: Saunders; 2003. p. 501–29.
43 Brubakk AO, Peterson R, Grip A, Holand B, Onarheim J, Segadal K, et al. Gas bubbles in the circulation of divers after ascending excursions from 300 to 250 msw. J Appl Physiol (1985). 1986;60:45–51. doi: 10.1152/jappl.1986.60.1.45. PMID: 3511026.
44 Tønjum S. Norwegian deep diving trials. Philos Trans R Soc Lond B Biol Sci. 1984;304(1118):143–9. doi: 10.1098/rstb.1984.0015.
45 Doolette DJ, Mitchell SJ. Biophysical basis for inner ear decompression sickness. J Appl Physiol (1985). 2003;94:2145–50. doi: 10.1152/japplphysiol.01090.2002. PMID: 12562679.
46 Doolette DJ, Mitchell SJ. Extended lifetimes of bubbles at hyperbaric pressure may contribute to inner ear decompression sickness during saturation diving. J Appl Physiol (1985). 2022;133:517–23. doi: 10.1152/japplphysiol.00121.2022. PMID: 35834629.
47 Van Liew HD, Burkard ME. Density of decompression bubbles and competition for gas among bubbles, tissue, and blood. J Appl Physiol (1985). 1993;75:2293–301. doi: 10.1152/jappl.1993.75.5.2293. PMID: 8307888.
48 Flook V. Excursion tables in saturation diving - decompression implications of current UK practice, Unimed Scientific Limited, Report: 244. 2004. [cited 2025 Sep 30]. Available from: https://webarchive.nationalarchives.gov.uk/ukgwa/20241208030054/https://www.hse.gov.uk/research/rrhtm/rr244.htm.
49 van Ooij PJ, Hollmann MW, van Hulst RA, Sterk PJ. Assessment of pulmonary oxygen toxicity: relevance to professional diving; a review. Respir Physiol Neurobiol. 2013;189:117–28. doi: 10.1016/j.resp.2013.07.014. PMID: 23886638.
50 Tetzlaff K, Thomas PS. Short- and long-term effects of diving on pulmonary function. Eur Respir Rev. 2017;26(143):160097. doi: 10.1183/16000617.0097-2016. PMID: 28356403. PMCID: PMC9489140.
51 Risberg J, van Ooij PJ. Hyperoxic exposure monitoring in diving: A farewell to the UPTD. Undersea Hyperb Med. 2022;49:395–413. doi: 10.22462/07.08.2022.1. PMID: 36446287.
52 Thorsen E, Kambestad BK. Persistent small-airways

dysfunction after exposure to hyperoxia. J Appl Physiol (1985). 1995;78:1421–4. doi: 10.1152/jappl.1995.78.4.1421. PMID: 7615450.
53 Suzuki S, Ikeda T, Hashimoto A. Decrease in the single-breath diffusing capacity after saturation dives. Undersea Biomed Res. 1991;18:103–9. PMID: 2042261.
54 Thorsen E, Segadal K, Stuhr LE, Troland K, Grønning M, Marstein S, et al. No changes in lung function after a saturation dive to 2.5 MPa with intermittent reduction in $PO_2$ during decompression. Eur J Appl Physiol. 2006;98:270–5. doi: 10.1007/s00421-006-0276-8. PMID: 16969641.
55 Shykoff BE, Lee RL. Risks from breathing elevated oxygen. Aerosp Med Hum Perform. 2019;90:1041–9. doi: 10.3357/amhp.5393.2019. PMID: 31748001.
56 Bardin H, Lambertsen CJ. A quantitative method for calculating pulmonary oxygen toxicity. use of the unit pulmonary toxicity dose (UPTD). Institute for Environmental Medicine, University of Pennsylvania, Pennsylvania, USA; 1971.
57 Risberg J, van Ooij PJ, Mátity L. Recovery from pulmonary oxygen toxicity: a new (ESOT) model. Undersea Hyperb Med. 2024;51:407–23. PMID: 39821770.
58 Arieli R. Pulmonary oxygen toxicity in saturation dives with $PO_2$ close to the lower end of the toxic range – A quantitative approach. Respir Physiol Neurobiol. 2019;68:103243. doi: 10.1016/j.resp.2019.05.017. PMID: 31158523.
59 DMAC. Improving diver safety – current medical issues. Report of a workshop held in October 2014. Aberdeen, UK; 2014. [cited 2025 Sep 30]. Available from: https://www.dmac-diving.org/guidance/DMAC-Workshop-20141008.pdf.

**Acknowledgments**

The authors thank the companies participating in this study for their support, and their representatives who reviewed the paper. In alphabetic order: Andy Butler (TechnipFMC), Cyrus Cama (POSH Subsea), Hadyn Stark (DCN Diving), Jeremy Starling (K Subsea), Tony French (RockSalt), Mark Hamilton (Boskalis), Michel Plutarque (Club des Anciens de Comex), Sean Brunton (Mc Dermott), Shane Ford (Shelf Subsea), Steve Ginn (DOF Subsea), Simon Binsted (Subsea7), Steve Sheppard (Helix Well Ops), Tomas Kristofferson (NDE Offshore), Torsten Lechler (Mermaid).

**Conflict of interest and funding**

The authors work for the offshore industry and sometimes for the participating companies. However, the study received no funding, and the review process remained independent.

**Submitted:** 22 July 2025
**Accepted after revision:** 25 November 2025