Review of saturation decompression procedures used in commercial diving

Jean-Pierre Imbert[1], Lyubisa Matity[2], Jean-Yves Massimelli[3], Philip Bryson[4]

[1] *Divetech, 1543 chemin des vignasses, 06410 Biot, France*
[2] *Hyperbaric and Tissue Viability Unit, Gozo General Hospital, Malta*
[3] *CHU de Nice, Hôpital Pasteur, 30 avenue de la voie romaine, 06001 Nice, France*
[4] *International SOS, Forest Grove House, Foresterhill Road, Aberdeen, AB25 2ZP, UK*

Corresponding author: *Jean Pierre Imbert, Divetech, 1543 ch des vignasses 0641Biot, France*
jpi.divetech@gmail.com

Keywords
Decompression tables; Occupational diving; Saturation diving

Abstract

(Imbert J-P, Matity L, Massimelli J-Y, Bryson P. Review of saturation decompression procedures used in commercial diving. Diving and Hyperbaric Medicine. 2024 31 March;54(1):23–38. doi: 10.28920/dhm54.1.23-38. PMID: 38507907.)

Introduction: This is a review of commercial heliox saturation decompression procedures. The scope does not include compression, storage depth or bell excursion dive procedures. The objectives are to: identify the sources of the procedures; trace their evolution; describe the current practice; and detect relevant trends.

Methods: Eleven international commercial diving companies provided their diving manuals for review under a confidentiality agreement.

Results: Modern commercial diving saturation procedures are derived from a small number of original procedures (United States Navy, Comex, and NORSOK). In the absence of relevant scientific studies since the late 80's, the companies have empirically adapted these procedures according to their needs and experience. Such adaptation has caused differences in decompression rates shallower than 60 msw, decompression rest stops and the decision to decompress linearly or stepwise. Nevertheless, the decompression procedures present a remarkable homogeneity in chamber PO_2 and daily decompression rates when deeper than 60 msw. The companies have also developed common rules of good practice; no final decompression should start with an initial ascending excursion; a minimum hold is required before starting a final decompression after an excursion dive. Recommendation is made for the divers to exercise during decompression.

Conclusions: We observed a trend towards harmonisation within the companies that enforce international procedures, and, between companies through cooperation inside the committees of the industry associations.

Introduction

Dr Albert Benkhe is credited with formulating the concept of saturation diving following the salvage of the crew of the USS Squalus submarine in 1942. The first human heliox saturation to 30 metres of seawater (msw) was performed at the Navy Experimental Diving Unit in 1963 following the Genesis Project of Dr George Bond.

Preliminary developments of saturation operations were undertaken in underwater habitats (Conshelf, Sealab, Tektite, Pre-Continent, etc.). Then, the technology evolved to saturation chambers installed on deck rather than on the seabed: logistics were easier; energy was directly supplied from the vessel. It became possible to abandon the site in bad weather.

The first commercial diving helium-oxygen saturation operations began in the late sixties. In 1965, the Undersea Division of Westinghouse Electric Corporation, under the direction of Jerry O'Neill and Alan Krasberg, carried out the first commercial saturation project for clearing the trash rack of the Smith Mountain dam at 61 m in Virginia. The system, called Cachalot, consisted of a large decompression chamber and a personnel transfer capsule, which could be mated to the chamber under pressure. In 1969, Comex carried out a saturation operation to 100 msw in the Gulf of Biscayne onboard the Astragale vessel.

In 1971, the Brent field was discovered at a depth of 140 msw exceeding the possibilities of surface-oriented diving. The installation of the North Sea platforms drove the development of heliox saturation diving and triggered the demand for qualified personnel. The first divers came from the navies, the only institutions at the time with a formal training scheme, and set the discipline that still prevails during dive supervision. American divers arrived from the Gulf of Mexico and brought along the fiberglass helmets, the hot water suits and the silver duct tape. This diversity of culture is the foundation on which saturation diving developed. The diving companies established associations such as the Association of Diving Contractors (AODC) and later the International Marine Contractors Association (IMCA), which turned saturation diving into a mature and efficient technology in less than ten years. By the 1980's, more than 6,000 divers were working in the North Sea and the 'North Sea Standards' ruled the offshore world.

However, the standardisation effort did not include heliox saturation procedures. In the 70s, safe and efficient saturation provided a commercial advantage over competition. Diving manuals were stamped 'Secret'. Even though companies are now developing numerous industrial guidelines, they continue to use different diving procedures.

A heliox saturation dive includes the following phases (Figure 1):

- The initial pressurisation or 'blowdown' of divers to target pressure corresponding to the storage depth. The pressurisation may include stops. Its duration is around 2 hours (h) for compression to 120 msw storage depth. It is significantly slower for saturations deeper than 180 msw to control high-pressure nervous syndrome (HPNS) and compression arthralgia.
- A minimal hold period after the divers arrive at storage depth and before they may start their first bell dive. This allows the divers to adapt to depth. The hold duration varies with storage depth: it is around 2 h at 120 msw storage depth.
- The 'bottom phase' during which the divers live in a chamber, at storage depth.
- The bell dives. Divers are transferred daily from the storage chamber to the dive site in the diving bell. The allowed excursion vertical distance depends on depth. It is around 20 msw at 120 msw storage depth.
- The final decompression to surface pressure. The initial phase is carried out with a constant chamber PO_2. The last phase proceeds from 15 msw to the surface with a constant chamber oxygen fraction. A typical decompression from 120 msw storage depth lasts five days.
- The saturation time is limited to 28 days by Diving Medical Advisory Committee (DMAC) guidance note 21.[1] This limitation may differ with local regulations, for instance in Norway.

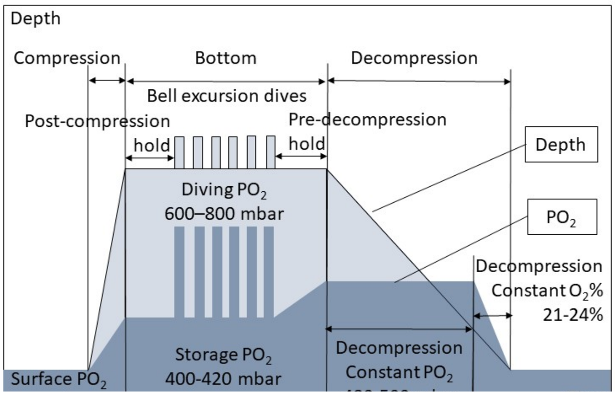
The purpose of this review is to document the current international saturation decompression procedures used in the offshore industry. The objectives are to 1) identify the source of the procedures, 2) trace their evolution, 3) describe the current practice and 4) detect any relevant trends.

Methods

SOURCES

The documentation related to the development of commercial diving in general, and saturation diving in particular, is dispersed, mainly located in company internal and restricted documents. The authors have been involved in commercial diving operations during their career. Non-referenced information in this review should be considered as sharing of personal experience. In particular, two authors worked for Comex and Stolt Comex Seaway and provided information on their historical diving manuals.

Figure 1
A typical commercial diving saturation showing depth profile and divers inhaled partial pressure of oxygen (PO_2); mbar – millibar



UNITS

The documents reviewed are operational procedures where depth is used instead of ambient pressure and where expressions such as 'shallower', 'deeper', 'ascending' or 'surface' are common terms. With editorial consent we deliberately kept this technical jargon for consistency. For the same reason:

- Gas partial pressures are expressed in mbar (1 mbar = 0.1 kPa). Gas fractions are expressed in percentages.
- Pressures are expressed in msw (1 msw = 10.0381 kPa according to EN 13319).
- Imperial units have been converted using 1 foot of seawater (fsw) = 0.30643 msw as specified in the US Navy diving manual. When procedures used both imperial and metric systems, only the provided metric values were considered.

DIVING COMPANIES

The IMCA website lists 50 companies that hold a certificate for 'unrestricted diving' which covers saturation diving. This number must be reduced to around 30 considering that some companies have multiple registrations. We selected 11 leading international companies for which we had connections through our professional activities. The conditions for participation were defined in a memorandum of understanding, signed by the authors and each diving company, stating that:

- The procedures could be used scientifically with the name of the company being unidentifiable.
- The company could review the final paper and retain the right to withdraw from the publication.

The eleven companies are:

- Boskalis, Papendrecht, The Netherlands
- DOF Subsea, Perth, WA
- Fugro, Singapore
- Helix Well Ops, Aberdeen, UK
- K Subsea, Singapore
- McDermott, Houston, Texas, USA
- Mermaid Subsea Services, Bangkok, Thailand
- Rever Offshore, Aberdeen, UK
- Shelf Subsea, Perth, WA
- Subsea7, Aberdeen, UK
- TechnipFMC, Aberdeen, UK

They are later de-identified as company A, company B, etc in an order unrelated to the above list. For each of these diving manuals received we associated a saturation procedure called procedure A, procedure B, etc. Note that we compared procedures in the range of 200 msw to surface, independently of the deepest storage depth specified in the manual. We excluded from the study any specific procedures used for deeper diving. We considered procedures in use in 2020 and disregarded any subsequent versions.

It should be noted that changes have occurred in the industry since 2022. Rever Offshore was taken over by the company Boskalis Subsea Services, but their procedures were reviewed by the former Rever Offshore diving manager. Fugro have ceased manned diving operations and no longer maintain their diving manuals. Simon Binsted, the former Fugro Diving Manager received authorisation from Fugro management to review this paper on their behalf.

HELIOX SATURATION DECOMPRESSION PROCEDURES

We focused on the final decompression of saturation dives for which we identified several operational characteristics:

- The minimal hold period at storage depth that is generally required after the divers have returned from their last excursion dive, before final decompression.
- An initial 'pull-up'. This corresponds to a rapid pressure drop equivalent to an upward excursion that was historically used to initiate decompression.
- The decompression protocol. The decompression generally takes place as a continuous pressure reduction ('continuous bleed'), or alternatively through incremental steps of typically 0.2–0.3 msw.
- The daily decompression period. Decompression can be continuous (24 h/24 h) or include interruptions for divers' comfort.
- These interruptions are called 'rest stops' by the US Navy. The rest stop can be set at a fixed time (at night for instance) or after a given daily decompression time. In that case, the time of the rest stop depends on the final decompression start time ('sliding rest stop').
- The chamber oxygen. The decompression starts with a constant chamber PO_2. However, the chamber oxygen fraction increases as the pressure decreases and must be limited to less than 23% because of the fire risk. A common chamber PO_2 of 500 mbar will exceed 20% at 15 msw. From 15 msw to surface, the decompression proceeds with a constant oxygen fraction.
- The decompression rates, which vary depending on depth ranges. The term 'decompression profile' characterises the distribution of decompression rates over depth.
- The daily decompression rate which is the pressure reduction achieved in 24 h, including rest hold periods.

ANALYSIS

We first studied the operational features of the decompression such as initial pull-up, decompression hold, daily rate of ascent, etc. We have compared decompression procedures from these companies as well as reference procedures such as:

- The procedures published in the regulations of Norway, Brazil and France.
- The procedures of the US Navy Diving Manual.
- The procedures from historical diving companies, Comex and Stolt Comex Seaway, for which two authors worked.

We then attempted to discuss the safety performances by using four endpoints:

- The decompression sickness (DCS) incidence recorded during operations.
- The venous gas emboli (VGE) grade measured during or after the decompression.
- The oxygen exposure and its level of pulmonary toxicity.

DIVER POPULATION

To characterise the diving population, at least in the frame of the North Sea operations, one of the participating companies provided the age distribution of 131 divers who rotated onboard one of their vessels in 1979.

It is the authors' view that saturation divers have significant experience; They traditionally start as air divers at 30 years old, move to saturation diving 10 years later and stay in the career. At the time of the study, the mean age of the saturation divers was 47 (range 30–61) (Figure 2).

Results

HISTORICAL REFERENCE PROCEDURES

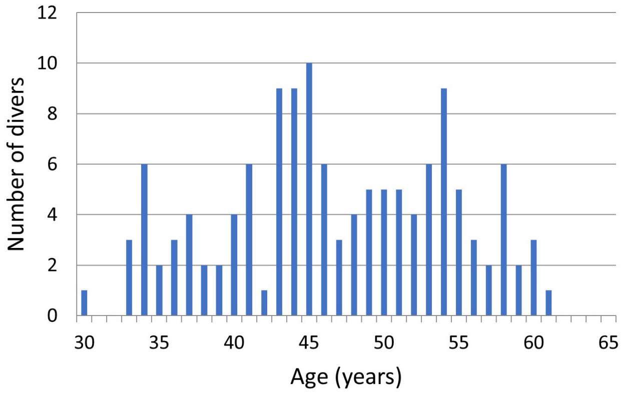
US Navy procedures

The US Navy saturation procedures were first published in the 1979 revision 2 of the US Navy Diving Manual.[2] They were characterised by:

- The possibility to initiate decompression by an ascending excursion.

Figure 2

Age distribution of 131 saturation divers working on a large North Sea diving support vessel



- A constant rate of decompression deeper than 60 msw and, varying rates from 60 msw to surface.
- Slow decompression rates and a low chamber PO$_2$ (350 to 400 mbar) until the fire risk zone is reached.
- A typical rest stop pattern during the decompression with a night stop from 00:00 to 06:00 and an afternoon stop from 14:00 to 16:00, leaving a total decompression time of 16 h per day.
- A chamber oxygen fraction controlled between 19% and 23% in the last metres of the decompression due to the fire risk.

The 2016 rev 7 US Navy Diving Manual brought few changes: the rates of decompression remained unchanged; the chamber decompression PO$_2$ was increased to 440–480 mbar; the timing of rest stop could be shifted depending on operational requirements.[3]

Comex procedures

Comex was a leading diving company during the 70's and 80's. This French company invested heavily in research and conducted a series of developments on deep diving in its Marseille hyperbaric center. Comex designed original diving procedures that have significantly influenced the industry.

The first Comex saturation manual was published by Dr Xavier Fructus in 1974 after the deep dives of the Sagittaire and Physalie experimental series. A system was set up to collect the dive logs into a database.[4] This database supported and monitored all the Comex procedure developments until 1994.

In their early versions, Comex saturation decompression procedures were characterised by:

- An oxygen protocol based on a 600 mbar chamber PO$_2$.
- A constant rate of decompression for a constant chamber PO$_2$ until the fire risk zone was reached.
- A continuous decompression with no rest stops.

In 1986, Comex conducted intensive research on decompression that initiated a large-scale revision of their diving manuals. The chamber PO$_2$ was reduced to 500 mbar for decompressions deeper than 155 msw. Later, in 1994, with the experience of the Norwegian contracts (Statoil, 3DP and Norsk Hydro Oseberg) and after the development of deep diving in Brazil, the 500 mbar PO$_2$ was standardised throughout the full depth range.

Seaway procedures

Seaway was a Norwegian company operating four diving vessels in the North Sea during the 80's. The Seaway 1984 saturation manual included procedures designed after the experimental dives DeepX I and II conducted at the Norwegian Underwater Technology Center (NUTEC) in Bergen. They were characterised by a constant rate of decompression with a constant chamber PO$_2$, similar to the Comex procedures. They had a rest stop set at a fixed time (00:00 to 06:00) and for the first time, a minimum 8 h hold before starting final or intermediate decompression. The Seaway procedures were representative of the Norwegian experience and later influenced the NORSOK standards (Norwegian acronym for "*the Norwegian shelf's competitive position*").

INTERNATIONAL REFERENCE PROCEDURES

Three countries, France, Norway and Brazil, have regulated diving to the level where ascent rates, rest stops, chamber PO$_2$, etc are specified for saturation. These regulations cannot be used directly for operations but build a strict frame for editing saturation procedures. We mention hereafter the French, Norwegian and Brazilian procedures in this context.

French saturation procedures

The 1992 revision of the French diving regulations was associated with the publication of official air tables and saturation procedures referred to as 'MT92'.[5] These procedures corresponded to the Comex 1986 diving manual and proposed two options for decompression: one with 600 mbar chamber PO$_2$ from storages depths not exceeding 155 msw and one with 500 mbar chamber PO$_2$ for deeper operations. These procedures have been used in France and in West Africa. The French diving regulations were revised in 2016 but no changes were made to the saturation procedures.

Norwegian saturation procedures

During the 80's, divers' unions in Norway raised the issue of commercial competition that could push companies to shorten decompression. In 1984, the Norwegian Petroleum Directorate (NPD) took a stand and contracted Dr Val Hempleman, from the British Royal Navy, to evaluate the saturation procedures in use and organise an international conference on the subject.[6] The NPD then initiated an action to standardise saturation procedures in the Norwegian sector.

Representatives from the Norwegian oil and gas industry, divers' unions and the AODC participated in:

- Assessing the practice of five diving contractors operating in the Norwegian sector.
- Proposing a common framework designed by a working group of experts putting together the most conservative features of existing commercial tables for diving down to 180 msw.

The frame conditions in the NPD report were included in 1999 in the first edition of the NORSOK U-100 standards for manned underwater intervention. Up to now, the NPD frame conditions have remained unchanged and the following revisions of the NORSOK U-100 have not affected the saturation specifications.[7]

The NORSOK procedures are a blend of the US Navy for the decompression, Comex for the excursions and Seaway for the decompression hold. The overall results are conservative procedures with reduced excursion distances, slow rates of decompression and restricted saturation times. Although they lack operational flexibility, they benefit from a good reputation among the divers' community as documented in a recent questionnaire survey of Petroleum Safety Authority (PSA).[8]

The NORSOK procedures specify a PO_2 for chamber decompression widely defined between 400 to 500 mbar. However, company A, which operates in the Norwegian sector, provided a copy of their Norwegian saturation procedures that use the higher end of this range. Because of the wide range of chamber PO_2 specified, the safety of these procedures depends on how they are being implemented.

Brazilian saturation procedures

In the 80's, the diving companies operating in Brazil were using their own rules in the absence of comprehensive Brazilian legislation. When deep operations started in the Campos field, Comex, which had been involved in two of the Norwegian deep development contracts, brought along its expertise and became highly influential.[9]

The first national diving legislation was published in 1988, closely aligned with the North Sea standards. It included saturation procedures based on the Comex manual. The Brazilian Navy then built a hyperbaric centre and validated the procedures through a series of onshore dives. Brazilian diving regulations NORMAM-15/DPC are now available as Rev. 2, 2016 and are characterised by:

- A continuous decompression without any rest stop.
- A constant decompression rate with a constant chamber 500 mbar PO_2 till 20 msw.

The NORMAM-15 procedures are freely accessible from the Brazilian regulations website.[10] Grounded in three decades of Brazilian deep diving experience, they have become an international reference.[11,12]

REVIEW OF COMPANY PROCEDURES

These procedures are summarised in Tables 1 to 4, along with the ones from the references already mentioned.

Discussion

SOURCES OF CURRENT SATURATION PROCEDURES

The US Navy procedures have played a major role in the development of commercial diving because they were readily and freely available at the time it all started. The diving managers liked to claim they were complying with the US Navy because it was an unchallenged reference. Companies have since gained experience and introduced their own modifications such as increasing the PO_2 during the decompression and restricting excursion distances during the bell dives. Yet procedures C, F, G, H, I and K (six out of 11 companies) still reference the 2016 Rev 7 edition of the US Navy Diving Manual as the source of their saturation procedures.

The Comex manual largely inspired the Brazilian NORMAM-15 procedures. It also influenced procedures A, B, D and E that include a constant rate of decompression from bottom to 15 msw (four out of 11 companies).

The source of company J procedures are unknown.

These reference procedures have been empirically modified by the companies in consultation with their respective diving experts (medical advisors, consultants, etc.). The authors have participated in several of these diving manual revisions. However, the rationale behind these changes has often been lost. Only companies A, B, C, D and K (five out of 11 companies) have formally compiled documents called 'Justifications' or 'Provenance' that trace and explain the evolution of their diving procedures.

STORAGE DEPTH PO_2

The procedures all specify a chamber PO_2 at storage depth set around 400 mbar (Table 1).

The PO_2 at storage depth is raised to avoid complications in the event of hypoxia due to improper mixing of oxygen and inert gases. However, two other reasons are identified.

The first reason is historical. In the early 70's, Comex mobilised a saturation system on the deck of the Choctaw I barge with an external regeneration system. The barge was experiencing bad weather, the system at 120 msw and the chamber PO_2 at 400 mbar, when a large wave swept the regeneration plant away. The 2-inch hoses burst and the pressure rapidly dropped inside the chambers. Divers started closing all the valves in panic, including the pressurisation valve, and the surface team had to use the bell pressurisation valve to re-establish the pressure. By that time, the chamber

Table 1

Pre-decompression procedures; *decompression can start with an upward excursion if the time spent at storage depth exceeds the equivalent decompression time; **for storage depths shallower than 61 msw, a 2 hour (h) hold is required after an upward excursion; ***after an extended excursion, the chamber must be recompressed to divers' deepest depth and divers have to hold for 8 h; Max – maximum; mbar – millibar; min – minutes; Min – minimum; msw – metres of seawater; N/A – not applicable; Opt – optimal

Group	Deepest storage depth available (msw)	Chamber storage PO_2 (mbar)			Initial saturation decompression with an upward excursion	Hold time (h) before decompression after a:			
		Min	Opt	Max		Downward normal excursion	Downward extended excursion	Upward normal excursion	Upward extended excursion
US Navy 1979	487	350		400	Permitted	0	N/A	0	N/A
Seaway 1984	304	380	400	420	Forbidden	8	N/A	8	N/A
Comex 1986 std	155	400	425	500	1 msw in 10 min	12	N/A	12	N/A
Comex 1986 deep	200	400	425	500	1 msw in 10 min	0	N/A	0	N/A
Comex 1994	300	300	400	500	1 msw in 10 min	0	12	0	12
France MT 1992	180				1 msw in 10 min	0	12	0	12
Brazil 2021	350				Forbidden*	0	12	0	12
US Navy 2016	350	440		480	Permitted**	0	N/A	0	N/A
NORSOK 2016	180	400		500	Forbidden	8	N/A	8	N/A
Company A	180	380	400	420	Forbidden	8	12	8	12
Company B	180	380	400	420	Forbidden	8	12	8	12
Company C	300	370	400	430	Forbidden	8	8***	8	8***
Company D	180	380	400	420	Forbidden	8	12	8	12
Company E	305	370	400	430	Forbidden	6	N/A	6	N/A
Company F	300	440	450	480	Forbidden	6	N/A	6	N/A
Company G	487	350	400	450	Forbidden	8	N/A	0	N/A
Company H	306	370	400	430	Forbidden	2	N/A	2	N/A
Company I	201	380	400	450	Forbidden	8	N/A	8	N/A
Company J	487	380	400	450	Forbidden	6	24	6	24
Company K	310	380	400	450	Forbidden	8	N/A	8	N/A

had dropped half of the initial pressure. Since then, the industry policy has been to set the storage PO_2 around 400 mbar so that the atmosphere could remain breathable if the pressure were to accidentally drop to half of its initial value.

The second reason is related to excursion dives. In case of an ascending excursion, the storage depth becomes the deepest depth. The storage depth PO_2 therefore influences the permitted excursion distance. If storage PO_2 and dive mix PO_2 are too different, ascending and descending excursions become asymmetrical. With modern procedures that use a sliding excursion window, a higher storage PO_2 provides a higher flexibility.

INITIAL 'PULL-UP'

The US Navy Diving Manual paragraph 13.23 allows starting a saturation decompression with an ascending excursion (initial pull-up), based on the concept of the diver's deepest depth, which directs the selection of saturation excursion distance. The excursion amplitude can be significant, as for instance, a 30 msw excursion from 120 msw to 90 msw. It is, however, specified that this initial pull-up remains within the discretion of the person in charge.

Even if the initial pull-up is limited, the problem is to measure the influence of this sudden pressure change on potential bubbles remaining from the last excursion dive and

Table 2
Rest stops during decompression; h – hours; msw – metres of seawater; N/A – not applicable

Group	Rest stop	Daily stop duration (h)	Daily decompression duration (h)	Shallow rest stops
US Navy 1979	Fixed	2 + 6	16	
Seaway 1984	Fixed	6	18	
Comex 1986 std	None	N/A	24	
Comex 1986 deep	None	N/A	24	
Comex 1994	None	N/A	24	
France MT 1992	None	N/A	24	
Brazil 2021	None	N/A	24	
US Navy 2016	Sliding	2 + 6	16	
NORSOK 2016	Fixed	6	18	Stop < 3 msw performed at 3 msw
Company A	Sliding	5	19	No stop between 15 msw and surface
Company B	Sliding	5	1	No stop between 15 msw and surface
Company C	None	N/A	24	
Company D	Sliding	5	19	No stop between 15 msw and surface
Company E	Sliding	4	20	No stop between 15 msw and surface
Company F	Sliding	8 (2 stops)	16	
Company G	Fixed	2 + 6	16	
Company H	Fixed	8	16	Stop < 3 msw ignored
Company I	Fixed	2 + 6	16	Option left for continuous decompression
Company J	None	N/A	24	
Company K	Sliding	2 + 6	16	Stop < 3msw performed at 3–4 msw

the impact of these bubbles on the following decompression. Flook used a bubble growth algorithm developed by Van Liew and Burkard to estimate this impact.[13] Flook modeled the bubble population after excursions and during saturation decompression and concluded that neither the excursion nor the decompression alone was likely to cause DCS. However, she pointed out that if a decompression was to follow an excursion with a too short interval, the residual bubble population from the excursion could interfere with the final decompression process and carried a risk.[14]

All the procedures reviewed have removed the possibility of starting a decompression with an ascending excursion.

DECOMPRESSION HOLD

Companies now specify a minimal time interval, called decompression hold, after an excursion dive, before starting a final decompression (Table 1). This decompression hold is only required after a descending excursion dive for procedures C and G. All the other procedures request a pre-decompression hold regardless of the type of excursion dive (nine out of 11 companies).

The hold duration varies from 2 h (procedure H), to 6 h (procedures E, F, J) and 8 h (procedures A, B, C, D, G, I and K, i.e., seven out of 11 companies). In practice, a few hours are needed to raise PO_2 inside the chamber before decompression and this hold has a minimal impact on the operations.

Note that Comex authorised a 1 msw ascent performed in 10 minutes at the start of the decompression but this was only intended to create a small pressure drop to seal the door of adjacent chambers. A similar procedure is proposed by company K.

Table 3

Decompression with constant chamber PO_2; the decompression rate is defined for the ascent between rest stops. The daily decompression includes the ascent phase and the rest stops. DDR – daily decompression rate; Deco – decompression; h – hours; Max – maximum; mbar – millibar; min – minutes; Min – minimum; msw – metres of seawater; Opt – optimal

Group	Chamber PO_2 (mbar)			Deco time (h)	Bottom–60 msw		60 msw–30 msw		30 msw–15 msw	
	Min	Opt	Max		Deco rate min·msw^{-1}	DDR msw·day^{-1}	Deco rate min·msw^{-1}	DDR msw·day^{-1}	Deco rate min·msw^{-1}	DDR msw·day^{-1}
US Navy 1979	350		400	16	32.6	29.4	39.2	24.5	49.0	19.6
Seaway 1984	500		530	18	36.0	30.0	36.0	30.0	36.0	30.0
Comex 1986 std	575		600	24	45.0	32.0	45.0	32.0	45.0	32.0
Comex 1986 deep	500		525	24	50.0	28.8	50.0	28.8	50.0	28.8
Comex 1994	480	500	500	24	50.0	28.8	50.0	28.8	50.0	28.8
France MT 1992	500		525	24	50.0	28.8	50.0	28.8	50.0	28.8
Brazil 2021	440		480	24	50.0	28.8	50.0	28.8	50.0	28.8
US Navy 2016	440		480	16	32.6	29.4	39.2	24.5	49.0	19.6
Norsok 2016	400		500	18	40.0	27.0	50.0	21.6	60.0	18.0
Company A	480	500	520	19	40.0	28.5	40.0	28.5	40.0	28.5
Company B	480	500	520	19	40.0	28.5	40.0	28.5	40.0	28.5
Company C	480	490	500	24	50.0	28.8	60.0	24.0	70.0	20.6
Company D	480	500	520	19	40.0	28.5	40.0	28.5	40.0	28.5
Company E	500	530	560	20	40.0	30.0	40.0	30.0	40.0	30.0
Company F		500		16	30.0	32.0	40.0	24.0	50.0	19.2
Company G	470	500	530	16	33.3	28.8	40.0	24.0	50.0	19.2
Company H		500	530	16	32.8	29.3	39.5	24.3	49.2	19.5
Company I		500		16	33.3	28.8	40.0	24.0	50.0	19.2
Company J	480	500	520	24	49.0	29.4	78.3	18.4	78.3	18.4
Company K		500		16	32.0	30.0	39.0	24.6	49.0	19.6

CHAMBER BLEED VERSUS STAGED DECOMPRESSION

Saturation decompressions are slow, e.g., a 90 min·msw^{-1} rate of decompression corresponds to 11 millimetres depth change every minute. They require continuous attention from the chamber operators. Operationally, two methods are available for decompressing the chamber:

- Continuous decompression (‘continuous bleed’) typically controlled by computers onboard modern diving support vessels.
- Staged decompression with repeated small decrements of depth.

Several procedures have been identified for staged decompression:

- Comex 1979 used an optional 1 msw step decrement with 10 min ascent time to the next stop when deeper than 50 msw.
- Procedure D proposes an optional 0.33 msw decrement as in US Navy Rev 7 procedures.
- Procedure F proposes an optional 5 msw step with 5 min ascent time to the next stop.
- Procedure K proposes an optional 0.2 msw step resulting in an ascent rate equivalent to continuous decompression using the last minute of the stop time to travel to the next stop depth.

A problem of staged decompression is what Comex divers used to call ‘passage de bulles’ during the step changes near the surface (literally translated as feeling bubbles passing by, or, alternatively, feeling ‘niggles’). Because the effect of Boyle’s law becomes more important close to the surface, it can be speculated these small but sudden pressure variations increase bubble volume, resulting in a greater likelihood to produce symptoms in whatever tissue in which they are present (such as periarticular connective tissue). The staged

Table 4

Decompression with constant chamber O2%; the decompression rate is defined for the ascent between rest stops. The daily decompression includes the ascent phase and the rest stops. DDR – daily decompression rate; h – hours; Max – maximum; min – minutes; Min – minimum; msw – metres of seawater; Opt – optimal

Group	Chamber O_2 %			15 msw to surface		
	Min	Opt	Max	Decompression rate min·msw^{-1}	Decompression time (h)	DDR msw·day^{-1}
US Navy 1979	21		23	65.3	16	14.7
Seaway 1984	21		22	80.0	18	13.5
Comex 1986 std	21		24	60.0	24	24.0
Comex 1986 deep	21		24	60.0	24	24.0
Comex 1994	21		24	80.0	24	18.0
France MT 1992	21		24	60.0	24	24.0
Brazil 2021		21		90.0	24	16.0
US Navy 2016	19		23	65.3	16	14.7
Norsok 2016	19		23	80.0	18	13.5
Company A	21	22	23	100.0	19	11.4
Company B	21	22	23	100.0	19	11.4
Company C	21	22	23	90.0	24	16.0
Company D	21	22	23	100.0	19	11.4
Company E	21	22	23	100.0	24	14.4
Company F		21	23	60.0	16	16.0
Company G		21	23	66.7	16	14.4
Company H		21	23	66.7	16	14.4
Company I	21	21	24	66.7	16	14.4
Company J	20	21	22	97.9	24	14.7
Company K	21		24	66.0	16	14.5

decompression option was removed in the later versions of the Comex manuals and the symptoms disappeared. The other companies only propose continuous chamber bleed (eight out of 11 companies).

REST STOPS VERSUS CONTINUOUS DECOMPRESSION

Rest stops were first defined in the US Navy Diving Manual as a daily interruption in the decompression process (or ‘night stops’ when stops take place during sleeping time). The justification presented at the time was to avoid divers sleeping in a cramped position that could reduce perfusion during decompression. Another story told was that in the early times, the US Navy doctors were annoyed by awakening every night and decided to stop decompression to get some sleep (personal communication with Dr Spaur).

We identified several rest stop patterns in our review (Table 2):

- Rest-stops set at fixed times identical to the US Navy pattern (00:00 to 06:00 and 14:00 to16:00) or the NORSOK pattern (00:00 to 06:00) as in procedures F, G, H and I (four out of 11 companies).
- A rest stop set after a given decompression duration that slides around the clock depending on the start decompression time (procedures A, B, D, E and K, i.e., five out of 11 companies)
- Continuous decompression without any rest stop (procedures C and J)

The stop durations vary from 4 h (procedure E) to 5 h (procedures A, B, D) and the classic US Navy 8 h split over two stops (procedures F, G, H, I, K, i.e., five out of 11 companies).

From our experience, when divers are asked their comments on rest stops, they typically provide the following answers:

- Stops prevent the 'popping' of my ears when I sleep in the last part of the decompression.
- Fixed stops permit synchronising back to normal day rhythm (for divers on night shift).
- I do not care, I sleep a lot anyway during decompression, at any time.

Operationally, rest stops set at a fixed time raise the problem of calculating the end decompression time because the number of rest stops depends on the start decompression time. Rest stops may also happen a few metres from the surface, causing technical problems (toilet no longer in operation, risk of sudden surfacing) and frustration. One way around this is to forbid rest stops shallower than 3 msw (procedures H and K) or to carry them out at 3 msw (procedure A). Another way is to remove any rest stop in the last 24 hours of the decompression and adapt the ascent rate accordingly, which corresponds to a slow and conservative end of decompression (procedures B, D, E and I).

Theoretically, rest stops reduce the daily time available for decompression. For a given daily decompression rate, rest stops require a faster rate during the active decompression phase. The question remains whether the recovery during the rest stop exactly balances the increase of the decompression rate during the ascent phase. No theoretical work could be found on the subject. In 1984, an attempt was made during the DeepX II experiment at NUTEC to compare the performances of the two methods of decompression. Three divers were decompressed continuously while another group of three divers were decompressed with rest stops, both groups with the same 24 h decompression rate. No difference could be documented.[15] A similar conclusion was derived from the Comex database (Imbert JP, presentation at the NPD conference, 1988).

The presence of rest stops therefore remains more a matter of company culture than a strategy for improving the decompression safety.

DECOMPRESSION RATES AND DURATIONS

Decompression rates are linked to the chamber PO_2 and govern the decompression duration. They have a critical operational and commercial importance (Table 3 and 4). Decompression rate patterns determine two characteristics of the decompression: duration and profile.

We calculated the decompression durations and the instructions specified in the procedures. We compared these decompression durations for several typical storage depths. Note that the final decompression duration may vary depending on the starting time (we used 06:00 in the program) and the conversion factor used for fsw and msw. We added the NORSOK procedures for comparison.

Table 5 and Figure 3 display the difference between the slowest and the fastest decompression durations. This difference reaches 25.7 h at 150 msw. However, Table 5 also indicates that for procedures A, B, C, D, E, F and H, this difference is less than 5 h over the 60–150 msw range. This means that seven out of 11 companies have very similar decompression durations.

We then plotted the daily decompression rate versus depth to compare the decompression profiles between procedures. Figure 4 shows that procedures have a similar decompression rate to 60 msw while there are greater differences in the shallower depths.

Deeper than 60 msw, all the procedures reviewed are characterised by a constant decompression rate. This has been a characteristic of the Comex saturation decompression since 1984 (and derived procedures like the NORMAM-15).[16] It is a consequence of the Comex method of calculation that used a safe ascent criterion based on Hennessy's critical volume assumption.[17] The same result can be obtained using Vann's model that predicts a linear relation between the rate of decompression and the PO_2.[18] This is also a consequence of the concept of extended oxygen windows.[19] According to these algorithms, the rate of decompression is a linear function of the PO_2 and should remain constant as long as the chamber PO_2 remains constant, regardless of depth.

The shallower part from 60 to 15 msw is also conducted with a constant PO_2 but reveals two practices, one with a constant decompression rate (as per the Comex algorithm), and the other with varying decompression rates (as per the US Navy tradition). The US Navy has never published the way their saturation decompressions were computed. It is likely that in the early 70's, they used trial and error and involved a combination of various models. This profile consisting of deep constant decompression rates and shallow varying decompression rates is typical of procedures that use the US Navy as parent procedures. It is also found in the NORSOK procedures that adopted this profile as a best practice at the time they were written.

INTERMEDIATE DECOMPRESSION

Projects often require intervention at various working depths. When depth variations exceed the possibilities of bell excursion dives, the storage depths can be adjusted by intermediate compressions and/or decompressions.

In the early time of North Sea installation, some clients insisted in decompressing divers during bad weather, based on the idea that they would be safer closer to the surface if the situation was to deteriorate. Divers could be subjected to a significant series of intermediate decompressions just because of bad weather. Following three intermediate decompressions in a row imposed on Comex divers by the November weather conditions in the Shetlands, the practice was eventually banned.

Table 5

Final decompression durations in decimal hours for several typical storage depths-for the companies. The pre-decompression hold is excluded from the decompression time. h – hours; msw – metres of seawater

Company	Decompression duration (h) by storage depth			
	60 msw	90 msw	120 msw	150 msw
A	60.0	85.0	110.0	135.0
B	60.0	85.0	110.0	135.0
C	59.0	83.0	107.0	131.0
D	60.0	85.0	110.0	135.0
E	59.0	83.0	107.0	131.0
F	65.5	88.5	111.5	134.
G	73.2	97.8	122.5	147.1
H	64.7	89.1	113.5	137.9
I	73.2	97.8	122.5	147.1
J	85.0	110.0	135.0	160.0
K	74.2	107.7	129.0	153.3
Range	59.0–85.0	83.0–110.7	107.0–135.0	131–160.0
Median	64.7	88.5	111.5	135.0
NORSOK	78.0	104.0	130.0	156.0

Figure 3

Decompression times in decimal hours for several typical storage depths, for the company procedures reviewed; the pre-decompression hold is excluded from the decompression time. std – standard

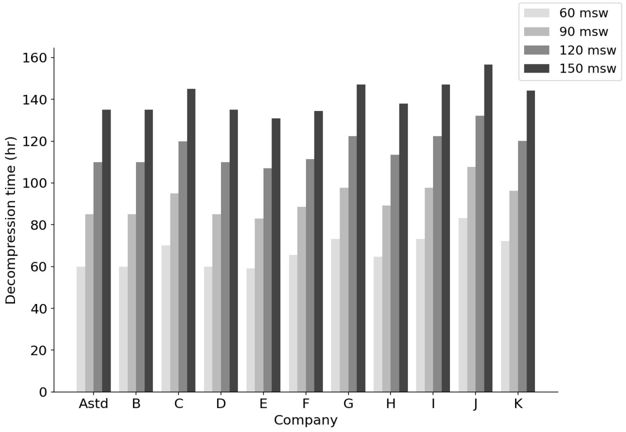
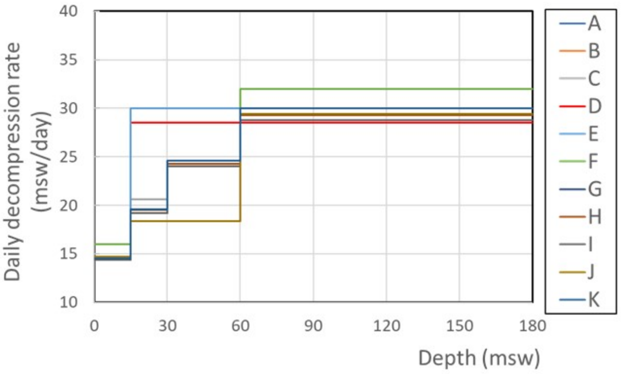


Figure 4

Daily decompression rate (msw·day^{-1}) versus depth (msw), for the 11 different procedures analysed



In 1986, Comex introduced a limitation to intermediate decompression based on the understanding that decompression was stressful and limitations should be based on a 'maximal acceptable dose'. The maximum dose was defined as a decompression distance of 200 msw, which corresponded to the deepest available storage depth in their manual. The principle was that this distance could be split into a series of intermediate decompressions. Intermediate decompressions could be cumulated as long as their total distance would not exceed 200 msw. The system could be 'pushed' beyond reasonable limits if multiple small intermediate compressions/decompressions were used (saw tooth-shaped profile).

Around the same time, another company, Rockwater, introduced a limitation based on the number of intermediate decompressions followed by a compression to a new storage depth, known as the 'W' profile (Figure 5). The W-profile was restricted to one intermediate decompression and one intermediate compression before final decompression. The system could also be 'pushed' by using an intermediate decompression/compression of high amplitude but many companies adopted it because of its simplicity.

Finally, in Norway, NPD referred to a publication from the Hades database to justify the notion that the dive planning should be based on minimum change of storage depths and excursion exposures. The NORSOK standards thus included the more restrictive rule of the 'V' profile where divers can work at intermediate storage depths during decompression but cannot be recompressed to any deeper storage depth.[20] This position was later judged as a misinterpretation by JE Jacobsen, one of the main authors of the Hades paper, during a presentation at a DMAC meeting in 2017.[21]

The review shows that current practice for limiting intermediate decompression is a mixture of the V, W profiles and Comex cumulative decompression distance.

EXERCISE DURING DECOMPRESSION

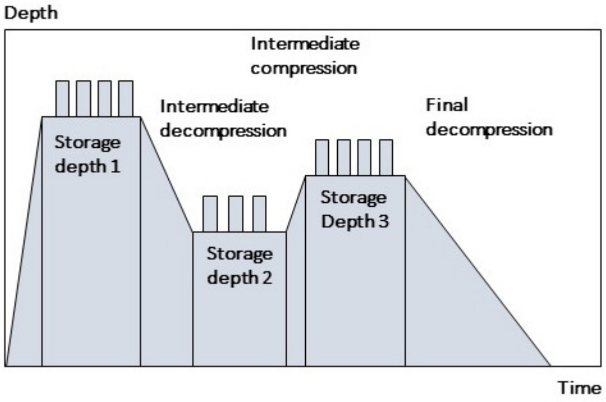
Exercise can be associated with muscle stretch, impacts on joints and vibrations. Preconditioning studies on divers have shown that exercise reduces VGE levels after the dive.[22,23] It has been postulated that vibrations and vasodilatation affect a pre-existing population of bubble precursors and therefore could reduce the source of bubble formation [24, 25]. On the other hand, Madden et al. showed that exercise after diving increases the incidence of bubbles appearing in the arterial circulation, possibly because of the increase in the pulmonary artery pressure.[26] It is therefore assumed that a light and measured exercise could be beneficial during decompression.

Such potential benefit was subjectively evaluated via a questionnaire survey performed in 2017 onboard a North Sea diving support vessel by one of the authors but not published in the associated paper.[27] Answers evoked a matter of lifestyle. Old divers are reluctant to exercise because, during their long careers, they have been consistently told that exercising is harmful. Younger and fitter divers exercise during decompression and claim that they feel and sleep better during this long boring period.

Our review has shown that eight out of 11 companies encourage divers to lightly exercise during the decompression. This takes the form of a small paragraph named good or healthy practice during decompression stating: "*Move around regularly. Do not maintain a cramped position that restricts blood circulation*" (procedures G,E and J). The more detailed form (procedure A for instance) specifies that the exercise must remain moderate such as steppers, bungees and static bicycles. In the absence of definitive scientific evidence, light exercise during saturation decompression remains a matter of diver's personal choice.

Figure 5

The 'W' rule used for storage depth adjustments during one saturation



PUBLISHED DECOMPRESSION SICKNESS INCIDENCE

The evaluation of the DCS risk in modern saturation operations is difficult. Companies do not share information. We did not request this information from the 11 companies participating in the study.

Among the historical procedures, Comex documented their safety performances with an exposure database and published their saturation diving track records. The average DCS incidence was 1.02% (59 DCS cases in 5,744 exposures) for dives performed using procedures described in the 1979 Comex manual.[28] It decreased to 0.54% (12 DCS in 2,200 exposures) for dives performed with Comex procedures later implemented in the French 1992 diving regulations (unreferenced report). All symptoms were exclusively articular pain, reported during the last metres of the ascent and never at surface.

Seaway also developed a database (Hades) for the monitoring of their diving operations.[20] In 1978, the results published for their saturation decompressions indicated an overall DCS incidence of 0.83% (22 DCS cases in 2,662 exposures,). As in the Comex database, all cases were articular pain occurring in the last part of the decompression.

The only modern source is PSA in Norway that has been collecting and publishing saturation safety records since 1990.[29] The cases are all recorded in the Norwegian sector and therefore associated with use of the NORSOK procedures. The site accessed on 21/09/2023 indicates one DCS case recorded since 2000. The corresponding incidence cannot to be evaluated because the exposures are expressed as men x hours in saturation and not saturation dives.

Finally, the diving manager of one of the participating companies indicated to the authors that DCS has become a rare event and stated "*we have not had a bend in the last 10 years*". This is in line with the authors' experience with other companies. Nowadays, across the industry, DCS is not observed in saturation diving.

MEASURED VGE GRADES

Venous gas emboli are commonly observed after asymptomatic dives using acoustic doppler or ultrasound imaging. Although the presence of VGE is by itself not predictive of DCS for a given diver, a statistical link is observed in surface-oriented diving between the amount of observed VGE in a group of divers and the incidence of DCS.[30,31]

Significant VGE grades were detected during deep saturation decompression in the experimental dives and operational dives conducted in Norway.[32,33] These high levels of VGE contrast with recent measurements performed during operations in the North Sea. In 2017, we monitored 49 saturation divers after decompression from 120 and 140 msw using echocardiography and detected no bubbles.[34] In 2022, we monitored 15 divers using ultrasound subclavian Doppler detection during and after saturation decompression from 40–50 msw storage depths, and found no bubbles.

Our experience with bubble monitoring is that high grades of VGE are no longer a concern in the saturation decompression we monitored, at least to 140 msw.

PULMONARY OXYGEN TOXICITY

Oxygen plays a major role during decompression. It increases the inert gas gradient between tissue and blood as well as the oxygen window and permits accelerating the decompression.[19] However, high levels of oxygen generate reactive oxygen species that interfere with normal cell functions. While central nervous system toxicity is not a concern in saturation diving, pulmonary toxicity can be a limiting factor.

The PO_2 should not be too low. An experimental saturation dive to 240 msw was conducted in Norway with slow decompression rates and reduced PO_2 during decompression (500 mbar during the day, 300 mbar during the 8 h night stop). No change in pulmonary function was observed. However, one case of DCS was recorded among the eight divers.[35] This suggests the difficulty of safely decompressing from saturation with a low oxygen level. Prof. Lambertsen had a definite position on the subject that he summarised as "*better cope with the effects of oxygen than with the ones of DCS*".[36]

On the other hand, a high PO_2 cannot be sustained for too long. Early saturation decompressions used a 600 mbar chamber PO_2 (Comex 1979) but when diving moved to deeper depths in Norway and in Brazil, longer decompressions raised the problem of pulmonary toxicity. The PO_2 was reduced to 500 mbar and the use of a 600 mbar PO_2 was restricted to less than 155 msw (Comex 1986 manual). Ultimately, a 500 mbar chamber PO_2 became the company standard for all depths.

Our survey has shown that while one company uses a chamber PO_2 of 530 mbar (procedure E), most companies use 500 mbar as an optimal value (procedures A, B, F, G, H, I, J and K, i.e., eight out of 11 companies) or 490 mbar (procedures C and D).

The divers' tolerance of pulmonary oxygen toxicity is difficult to measure and predict.[37] The industry approach was based on 'units of pulmonary toxicity dose' (UPTD) because of their simplicity.[38] However, it has been shown that the UPTD dose is not an appropriate tool for measuring oxygen toxicity, in surface oriented diving.[39]

Arieli developed a dose index accounting for recovery and validated it against a sample of saturation exposures.[40] However, given the paucity of exposure data at the lower end of the hyperoxic spectrum, the model remains to be validated for operational use in saturation diving. It is therefore currently not possible to reliably estimate a pulmonary toxic threshold dose for the company procedures.

It must be noted that the higher PO_2 to which the divers are exposed is the one used during the bell dives, for six continuous hours, daily. Therefore, most of the hyperoxic exposure takes place during the bottom phase.

It appears that the PO_2 used in current saturation procedures is the result of successive empirical adjustments and a better understanding of both the excursion and decompression design. Hence, the oxygen toxicity dose calculations could help optimising the diver's hyperbaric oxygen exposure.

EVOLUTION OF SATURATION PROCEDURES

In the 70's, navies, universities and governments conducted research and provided diving procedures to the industry. The last large research led by the industry was the Norwegian deep diving program of the 80's. Today, companies rely on themselves to improve their diving procedures.

The drive for such changes is no longer DCS occurrence but instead, the need for more flexible procedures. Managing operations of large and expensive diving vessels requires options and alternatives.

The ethical principles and the practical procedures for the development of decompression tables, were published by the Undersea Medical and Hyperbaric Society in the conclusions of a workshop on validation of decompression tables, in 1987.[41] These conclusions have been since considered as the reference for developing and improving decompression procedures. The principles developed in these conclusions are based on small step changes and careful evaluation. They include the following activities:

1. Evaluation of the latest scientific and medical information.

2. Definition of the models. Publication of the new procedures.
3. Monitoring operations to identify areas of improvement of the provisional procedures.
4. Validating the changes on selected worksites under controlled conditions before acceptance.
5. Review and analysis of data collected.
6. Approval of the new procedures or reiteration.

These principles are in line with the industry procedures of management of change that also stress the importance of validation and monitoring. They provide referenced standards permitting the companies to monitor and improve their diving procedures.

TRENDS

We have seen discrepancies between procedures. Table 5 shows a difference of 25.7 hours between the slowest and the fastest decompression time from 150 msw storage depth. However, as discussed during the DMAC 2014 meeting in Aberdeen, we do not have any information that would enable us to evaluate the consequence of these differences on the divers' health.[42]

We have also observed a convergence within procedures (moving towards similar PO_2, similar daily decompression rates, similar pre-decompression holds, etc.). Table 5 also shows that for seven companies, there is less than 5 h difference in the decompression time from 60 to 150 msw storage depth.

Because no large-scale research project has been conducted since the Norwegian deep diving contracts, we identified three ways the company procedures have evolved through:

- Internal evolution based on empirical adjustments. This is facilitated by freelance personnel freely moving between companies and carrying along their knowledge and experience.
- Forced evolution after takeovers and mergers between companies.
- Guided evolution by regulations, industry standards and client's requirements.

These evolutions have been made possible by the sharing of the company experiences within the industry associations such DMAC, IMCA and the International Association of Oil and Gas Producers (IOGP).
From this analysis, we foresee two possible paths for this evolution: standardisation and harmonisation:

- Standardisation assumes a stakeholder's association, i.e., contractors or clients, that defines, endorses and publishes policies. As opposed to government authorities, such associations have the capacity to rapidly adapt and change their policies.
- Harmonisation results from free adhesion to a practice. It supposes a consensual objective and sharing of scientific evidence, experiences and policies. Harmonisation is likely to continue with the internationalisation of the offshore industry.

KNOWLEDGE GAP

We believe that saturation procedures will continue to evolve and that this evolution must be supported by scientific research. Our experience is that divers' monitoring, which part of the Undersea and Hyperbaric Medical Society recommendations, brings valuable support to this evolution.

Commercial diving faces, at least two physiological challenges:

- The ageing of the population of divers and their capacity to cope with the various diving stresses.
- The oxygen partial pressures during saturation dive. We said that accurate models are required to evaluate pulmonary oxygen toxicity dose over a saturation. This dose must be managed considering that the bell excursion dives expose the divers to high PO_2's and this impacts the use of oxygen in decompression.

Companies seek flexibility to manage the modern and expensive diving support vessels that keep moving from one contract to the other. They need instructions on how to deal with these multi project campaigns that periodically change the working depths. They seek clear guidance for using all the possibilities of intermediate decompressions and ascending/descending/extended excursions.

Companies also need guidance in managing divers' rotation onboard these vessels. It is known that saturation diving is associated with endothelial dysfunction and inflammatory stress, followed by a recovery.[34,43,44] Hence, the way the divers manage their careers, alternating saturations and rest periods, is important. The DMAC note 21 seems to provide adequate guidance in managing saturation duration and between dive intervals since we noted in the sample diver's population that a 61-year-old diver can still obtain his saturation diving certificate. However, it is believed that more information is required to combine saturation diving and air diving, standard diving and deep diving, etc.

Conclusions

Eleven leading diving companies have provided their saturation procedures under a confidentiality agreement.
The comparison of procedures shows that:

- Current saturation procedures are derived essentially from the US Navy, Comex and NORSOK procedures.
- Diving companies have since empirically modified these procedures according to their needs and experience. This explains discrepancies like rest stops versus continuous decompression, intermediate decompression limitations and decompression holds.
- Chamber PO_2 settings and decompression rates

exhibit a surprising homogeneity, probably due to the convergence of independent efforts for improvement, clients' requests and requirements from regulations.

The review reveals trends:

- An ongoing harmonisation of procedures, based on the company systems for management of change and influenced by the internationalisation of the offshore industry.
- DCS has become a rare event for the companies participating in this review.
- Companies seek a higher flexibility for the management of modern diving support vessels. They need guidance pertaining to intermediate decompressions.

Finally, we believe that the companies need to seek scientific expertise to address pending physiological problems:

- Evaluation of the impact of an ageing population of divers.
- Optimisation of inspired oxygen pressure during saturation.
- Guidance on how to manage intervals between saturation and air diving, standard saturation and deep diving.

References

1 DMAC. Guidance note 21, rev 2. The duration of saturation exposures and surface intervals following saturations. 2006 June. [cited 2023 Dec 5]. Available from: https://www.dmac-diving.org/guidance/DMAC21.pdf.

2 US Navy Diving Manual Change 2. Mixed gas diving. NAVSEA 0994-LP-001-9010. Washington (DC): US Department of the Navy; 1977. [cited 2023 Dec 5]. Available from: https://apps.dtic.mil/sti/tr/pdf/ADA112710.pdf.

3 US Navy Diving Manual, Revision 7. NAVSEA 0910-LP-115-1921. Washington (DC): US Department of the Navy; 2016. [cited 2023 Dec 5]. Available from: https://diving-rov-specialists.com/index_htm_files/docs-14-usn-manual-rev7.pdf.

4 Imbert JP, Montbarbon S. Use of the comex diving data base. In: Sterk W, Hamilton, RW, editors. Proceedings of the European Underwater and Biomedical Society workshop on operational dives and decompression data: collection and analysis; 11-18th August 1990. Amsterdam, The Netherlands: EUBS; 1990. p. 122–32.

5 Mesures particulières de protection applicables aux scaphandriers. Imprimerie du Journal Officiel, 26 rue Desaix, 75732 Paris cedex 15: Bulletin Officiel du Ministère du Travail; 1992. [cited 2023 Dec 5]. Available from: https://diving-rov-specialists.com/index_htm_files/history-27-french-decree-30-october-2012.pdf.

6 Hempleman V. The safety evaluation of saturation decompression tables. Norwegian Petroleum Directorate; 1986. Report No.: I82-7527-203.6. [cited 2023 Dec 5]. Available from: https://www.ptil.no/contentassets/350fcc45128449329b7b92c78f6100a4/hempelman---safety-evaluation-of-saturation-decompression-tables-1986.pdf.

7 NORSOK. U-100 Manned underwater operations. Fifth ed, corrected version 2016-05-09. 2015. [cited 2023 Dec 5]. Available from: https://standard.no/en/sectors/petroleum/norsok-standards/u-underwater-op/u-100manned-underwater-operationsedition-5-december-2015-corrected-version-2016-05-09/.

8 Trend in risk level (RNNP). Report 2023. Norway. [cited 2023 Dec 5]. Available from: https://www.ptil.no/en/technical-competence/rnnp/

9 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; 15-17th September. Bergen: Norway; 2005. [cited 2023 Dec 15]. Available from: https://www.nui.no/open-nui-reports/.

10 Normam-15 DPC, Atividades Subaquáticas, Capitulo 11 Tabelas de mergulho, rev 2. 2016. [cited 2023 Dec 5]. Available from: https://www.marinha.mil.br/dpc/normas.

11 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.

12 Cadieux C. Diving management study no 5: Implement Normam 15/DPC saturation diving procedures. [cited 2023 Dec 5]. Available from: https://diving-rov-specialists.com/docs-diving-rov-specialists.htm.

13 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.

14 Flook V. Excursion tables in saturation diving - decompression implications of current UK practice. Unimed Scientific Limited, 2004. Report No.: 244. [cited 2023 Dec 5]. Available from: https://www.hse.gov.uk/Research/rrpdf/rr244.pdf.

15 Peterson RE, Segadal K. Deep Ex 80: Project IX. Compression / decompression. NUTEC, December 1980. Report No.: 52/80. [cited 2023 Dec 15]. Available from: https://www.nui.no/open-nui-reports/.

16 Imbert JP. Commercial diving. In: Balestra C, Germonpré P, editors. The science of diving: things your instructor never told you. London, UK: Lambert Academic Publishing; 2014. p. 118–36.

17 Hennessy TR, Hempleman HV. An examination of the critical released gas volume concept in decompression sickness. Proc R Soc Lond B Biol Sci. 1977;197(1128):299–313. doi:10.1098/rspb.1977.0072. PMID: 19749.

18 Vann RD. Decompression from saturation dives. In: Cox F, editor. Proceedings of the 3rd annual Canadian ocean technology congress, 1984. Toronto, Canada: 1984. [cited 2023 Dec 5]. Available from: https://apps.dtic.mil/sti/pdfs/ADA151743.pdf.

19 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.

20 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.

21 DMAC. Minutes of the 14th November 2017 Meeting. [cited 05/12/2023]. Available via request from: Info@dmac-diving.org.

22 Germonpré P, Pontier JM, Gempp E, Blatteau JE, Deneweth S, Lafère P, et al. Pre-dive vibration effect on bubble formation

after a 30-m dive requiring a decompression stop. Aviat Space Environ Med. 2009;80:1044–8. doi: 10.3357/asem.2588.2010. PMID: 20027852.

23 Balestra C, Theunissen S, Papadopoulou V, Le Mener C, Germonpré P, Guerrero F, et al. Pre-dive whole-body vibration better reduces decompression-induced vascular gas emboli than oxygenation or a combination of both. Front Physiol. 2016;7:586. doi: 10.3389/fphys.2016.00586. PMID: 27965591. PMCID: PMC5127795.

24 Gempp E, Blatteau JE. Preconditioning methods and mechanisms for preventing the risk of decompression sickness in scuba divers: a review. Res Sports Med. 2010;18:205–18. doi: 10.1080/15438627.2010.490189. PMID: 20623437.

25 Imbert J, Egi S, Germonpré P, Balestra C. Static metabolic bubbles as precursors of vascular gas emboli during divers' decompression: a hypothesis explaining bubbling variability. Front Physiol. 2019;10:807. doi: 10.3389/fphys.2019.00807. PMID: 31354506. PMCID: PMC6638188.

26 Madden D, Lozo M, Dujic Z, Ljubkovic M. Exercise after SCUBA diving increases the incidence of arterial gas embolism. J Appl Physiol (1985). 2013;115:716–22. doi: 10.1152/japplphysiol.00029.2013. PMID: 23766500.

27 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.

28 Imbert J, Bontoux M. Diving data bank: a unique tool for diving procedures development. Proceedings of the 20th Annual Offshore Technology Conference; 2-5th May, 1988. Houston, Texas, USA: Offshore Technology Conference; 1988. [cited 2023 Dec 5]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-b_17-diving-data-bank-a-tool-for-diving-procedrues-development.pdf.

29 Rapport fra ptil's dykkedataabse dsy. [cited 2023 Dec 5]. Available from: https://www.ptil.no/contentassets/7284426234ae40cdaa62e2037ed2bf35/dsys_2022-rapport.pdf.

30 Doolette DJ. Venous gas emboli detected by two-dimensional echocardiography are an imperfect surrogate endpoint for decompression sickness. Diving Hyperb Med. 2016;46:4–10. PMID: 27044455. [cited 2023 Dec 5]. Available from: https://dhmjournal.com/images/IndividArticles/46March/Doolette_dhm.46.1.4-10.pdf.

31 Nishi RY, Brubakk AO, Eftedhal OS. Bubble detection. In: Brubakk AO, Neumann TS, editors. Physiology and medicine of diving. 5th ed. London, UK: Saunders; 2003. p. 501–29.

32 Thorsen E, Hjelle J, Segadal K, Gulsvik A. Exercise tolerance and pulmonary gas exchange after deep saturation dives. J Appl Physiol (1985). 1990;68:1809–14. doi: 10.1152/jappl.1990.68.5.1809. PMID: 2361882.

33 Risberg J, Brubbak OA, Vangsnes T, Ferguson S, Eftedal O, Kambestad B, et al. Project P11324. Doppler monitoring under decomprejon fra operasjonelle metningsdykk. NUTEC 1994. Report No.: 44-93, Rev 2. [cited 2023 Dec 15]. Available from: https://www.nui.no/open-nui-reports/.

34 Imbert JP, Egi SM, Balestra C. Vascular function recovery following saturation diving. Medicina (Kaunas). 2022;58(10):1476. doi: 10.3390/medicina58101476. PMID: 36295636. PMCID: PMC9610043.

35 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.

36 NPD Conference on the health examination of divers – fitness to dive – decompression – use of oxygen. Stavanger, Norway; 1988.

37 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.

38 Bardin H, Lambertsen CJ. A quantitative method for calculating pulmonary oxygen toxicity. use of the unit pulmonary toxicity dose (UPTD). Pennsylvania, USA: Institute for Environmental Medicine, University of Pennsylvania; 1971.

39 Risberg J, van Ooij PJ, Matity L. From UPTD to ESOT: monitoring hyperoxic exposure in surface-oriented diving. Undersea Hyperb Med. 2023;50:301–6. PMID: 37708063.

40 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;268:103243. doi: 10.1016/j.resp.2019.05.017. PMID: 31158523.

41 Schreiner HR, Hamilton RW, editors. 37th Workshop of the UHMS. Validation of decompression tables; 1987 Feb 13-14. Bethesda (MD): UHMS; 1987. [cited 2023 Dec 5]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-b_71-validation-decompression-tables.pdf.

42 DMAC. Improving diver safety – current medical issues. Report of a workshop held in October 2014. Aberdeen, UK: DMAC; 2014. [cited 2023 Dec 5]. Available from: https://www.dmac-diving.org/guidance/DMAC-Workshop-20141008.pdf.

43 Brubakk AO, Ross JA, Thom SR. Saturation diving; physiology and pathophysiology. Compr Physiol. 2014;4(3):1229–72. doi: 10.1002/cphy.c130048. PMID: 24944036.

44 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):7118. doi: 10.3390/ijerph17197118. PMID: 32998440. PMCID: PMC7579105.

Acknowledgements

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), Allan Nairn (Mermaid), Jerry Starling (K Subsea), John Duncan (Subsea7), Keith Brockbank (Rever Offshore), Mark Hamilton (Boskalis), Michel Plutarque (Club des Anciens de Comex), Mike Paton and Steve Ginn (DOF Subsea), Sean Brunton (McDermott), Shane Ford (Shelf Subsea), Simon Binsted (Fugro), Steve Sheppard (Helix Well Ops).

Conflict of interest and funding

The authors work as consultants to the offshore industry and sometimes for the participating companies. However, the study received no funding.

Submitted: 25 July 2023
Accepted after revision: 26 January 2024