	Title of report: **Compression and excursion parameters for saturation dives 0-250 msw**

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Summary:

The NORSOK U-100:2015 standard stipulate requirements for off-shore diving. Subclause 8.2 in this standard list operational requirements, including helium-oxygen (heliox) saturation diving parameters. Some of these parameters are based on a report issued in 1991, and the recommendations has not been formally reviewed since. The Petroleum Safety Authority Norway (PSA) contracted NUI to complete this review with the objective to identify and compare a selection of commercial heliox saturation compression and excursion procedures for diving to a maximum of 250 msw. The study has compared three commercial procedures in addition to four public statutory provisions. Compression and excursion parameters are presented in tables and figures. While the comparison of the procedures and standards disclose significant variation in compression rates and excursion ranges, there is no outcome data suggesting superiority of one procedure to another. Divers may suffer the high pressure nervous syndrome (HPNS) during compression which may last well into the storage periods of deep dives, particularly if compression rate is too fast. There is no data suggesting that compression rates reviewed in this work will cause excessive HPNS for depths not exceeding 250 msw. Excursion ranges should be adjusted to minimize incidence of decompression sickness (DCS). The PSA database DSYS has not registered DCS in saturation diving on the Norwegian Continental Shelf since 2002. There is a paucity of reports detailing DCS in saturation diving under other national legislations, but verbal feedback from the diving contractors suggests that there is a very low DCS incidence. Data suggesting that any of the reviewed excursion ranges are unsafe have not been identified. Mathematical modelling suggests, however that reducing the pre-decompression hold periods after excursions may cause DCS. There is a paucity of data supporting NORSOK U-100:2015 restrictions on ascending excursions and the very narrow excursion ranges for shallow saturation diving.

Key Words in English: Saturation diving Compression HPNS Excursion procedures	Key Words in Norwegian: Metningsdykking Kompresjon HTNS Ekskursjonsprosedyrer

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1 Introduction and background

The Petroleum Safety Authority Norway (PSA) holds the regulatory responsibility for supervision of practically all heliox saturation diving in Norway. In their guidance to statutory regulations, PSA refers to the NORSOK standard U-100[1] for detailed requirements and recommendations related to planning and execution of such diving. NORSOK U-100:2015 (NORSOK) subclause 8.2 lists various operational requirements including frame conditions for compression, excursion and decompression of heliox saturation dives. These frame conditions were originally published in a Norwegian Petroleum Directorate report[2] in 1991. The frame conditions were defined by comparison of heliox saturation diving procedures from five different diving contractors. The most conservative procedure was chosen, but the report doesn't discuss the background for the decisions. The report has not been updated since and the frame conditions were incorporated in the NORSOK standard in 1999. The supervisory position of the Norwegian Petroleum Directorate was transferred to the PSA in 2004, and PSA initiated the present work to update the knowledge base related to heliox saturation compression and excursion parameters.

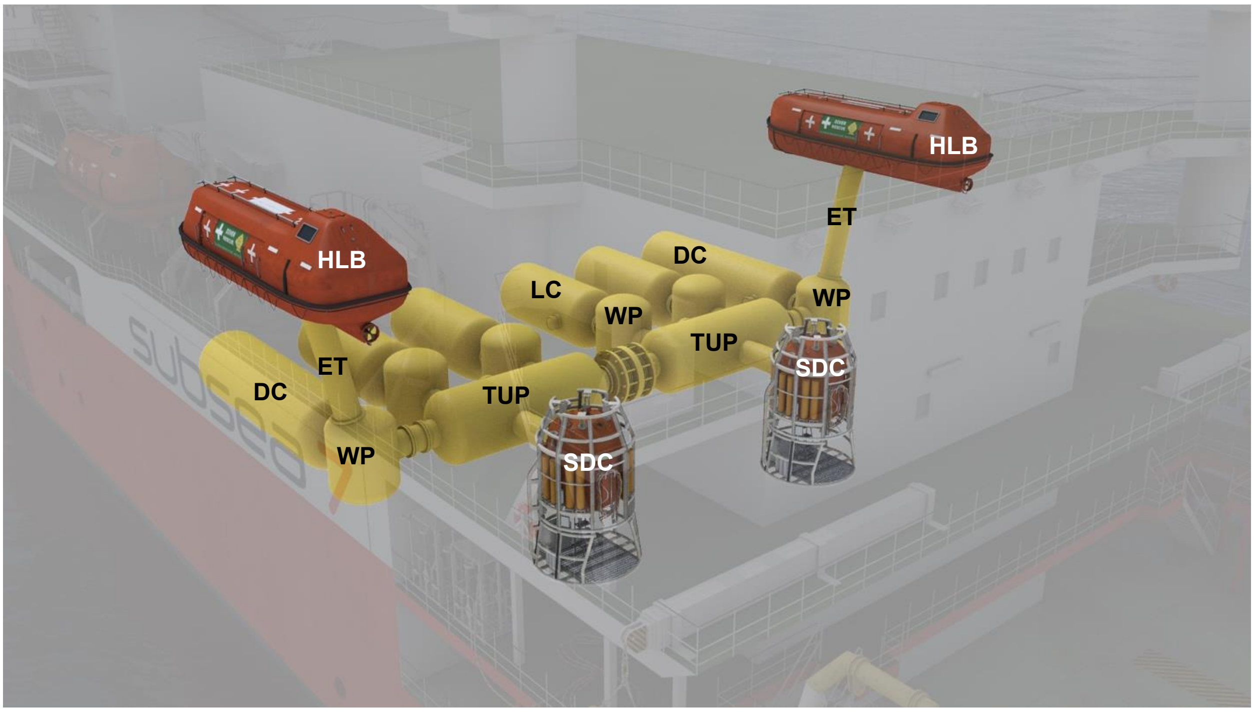

Figure 1 Illustration of a modern saturation diving system installed on a diving support vessel (DSV). Four living chambers (LC), six wet pots (WP), two diving bells/submersible diving chambers (SDC). The divers will normally occupy the living chambers at storage depth and use toilet and shower in the attached wet pots. They will be transferred to the diving bell through transfer-under-pressure (TUP) chambers. After finished storage period, they will be decompressed in the decompression chamber while a new team of divers will be compressed in the living chambers. In smaller saturation systems the living chamber may serve for habitation during storage as well as decompression and this chamber may be constructed as a twin lock with one lock serving as a wet pot. Two hyperbaric lifeboats (HLB, also termed self-propelled hyperbaric lifeboats (SPHL) are attached to the system by means of an escape trunk (ET) to allow safe evacuation of the divers in an emergency. Illustration credit Subsea 7.

2 Objective and scope

The objective was to identify and compare environmental parameters of the compression and bottom phase including pressure variations (excursions) of the bottom phase. The scope of this work was restricted to helium-oxygen (heliox) saturation dives to depths in the range 0-250 msw. The scope did not include decompression parameters.

Data should be retrieved from commercial diving contractors as well as procedures, regulations and standards published in the public domain.

3 Terms, definitions, and abbreviations

We have used terms in agreement with industrial practice[1]. Examples of saturation profiles are presented in Figure 2 and Figure 3. Increase of ambient pressure, the compression phase, takes place in the saturation living chamber and may include hold periods at defined pressure levels before the pressure at first storage depth is reached. The divers may be required to stay at storage depth for a stabilization time before they start wet diving.

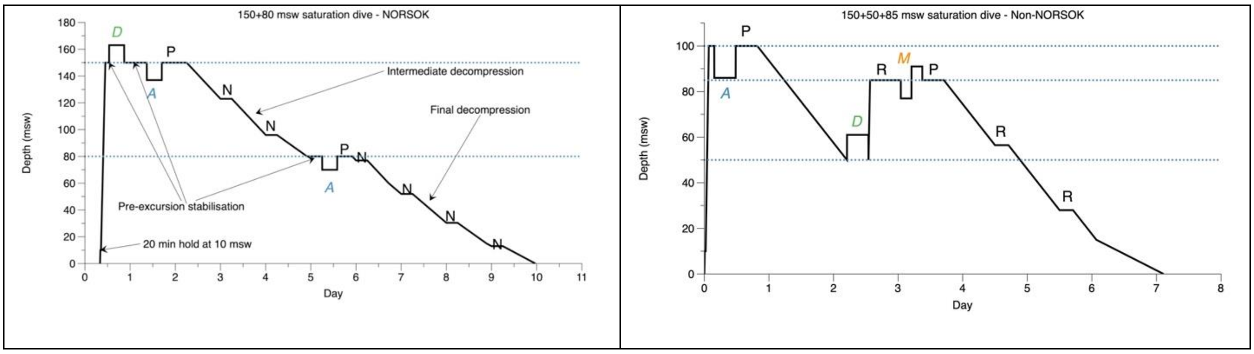

Figure 2 Examples of saturation diving pressure profiles with two or three storage levels (dotted lines). A: Ascending excursion D: Descending excursion M: Mixed excursion N: Night stop P: Pre decompression hold period R: Rest period. Left panel: Profile compliant with NORSOK[1]. Right panel: Profile applicable for non-NORSOK regulated diving.

A bell-run is defined as the period the diving bell is clamped off the chamber. The diver's time in water, outside the bell, is termed lock-out. If the pressure inside the bell is reduced or the diver ascends to a shallower depth this is termed an ascending excursion. A pressure increase within the bell or the divers descent to a deeper depth is termed a descending excursion. If the pressure and/or water depth is both increased and decreased during the same bell run this is termed a mixed excursion. The maximum allowed pressure increase and decrease is termed excursion window or excursion range.

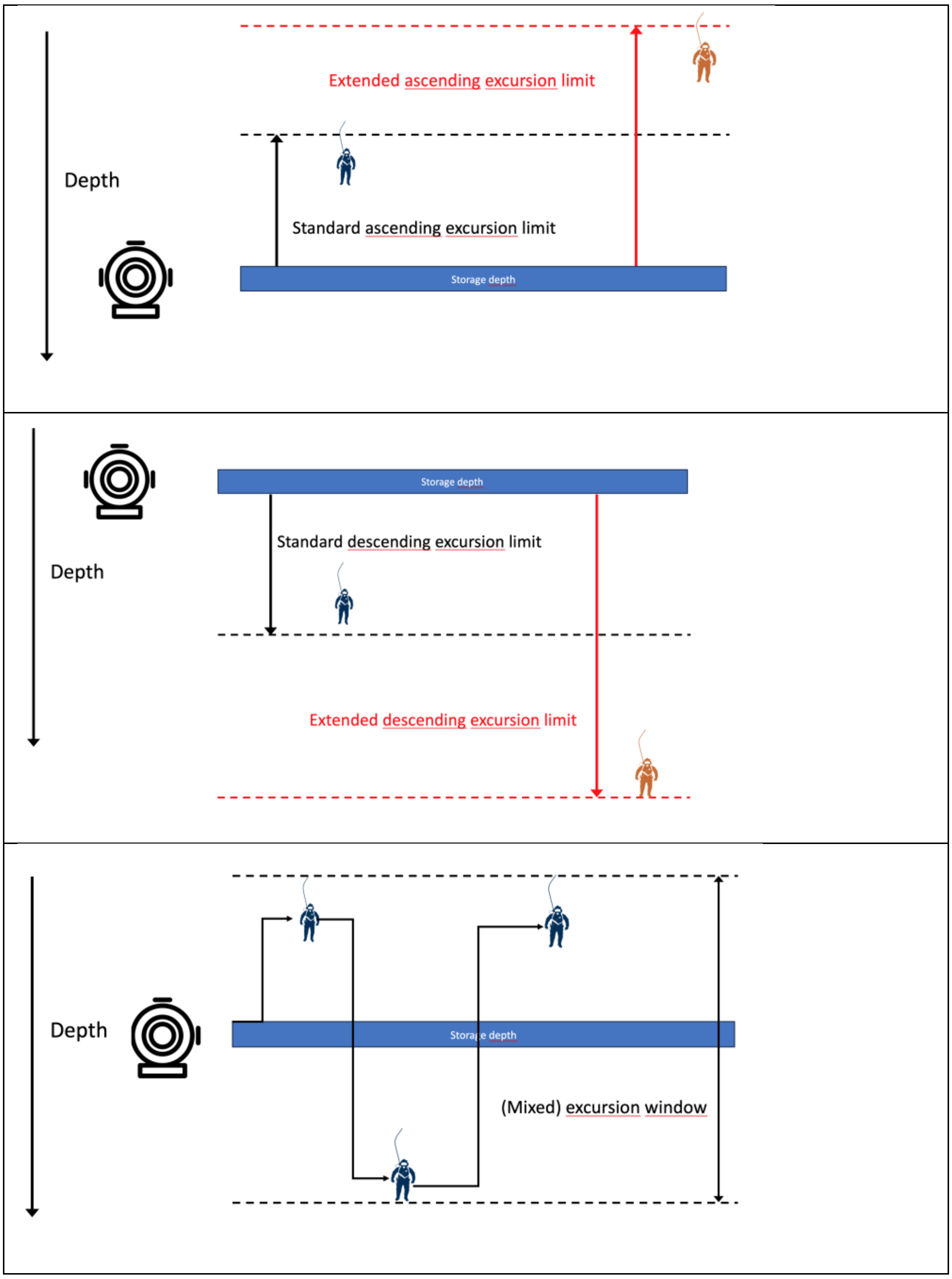

Figure 3 Examples of excursions during saturation diving. Except during bell runs, the diver will occupy the living chamber saturated at a stable storage depth. During dry bell runs and when immersed, the diver experience change in ambient pressure. This may be pressure reduction (ascending excursion, top panel), pressure increase (descending excursion, mid panel) or combined pressure increase and increase (mixed excursion, bottom panel). Standard excursions with least restrictions shown with black arrows, extended excursions calling for additional restrictions shown with red arrows. The maximum allowed limit for pressure increase and decrease is termed excursion range or excursion window.

The divers may be required to respect a hold period before decompression begins. This decompression may be an intermediate decompression to a shallower storage depth. The final decompression is the one completing the hyperbaric exposure by reaching surface.

Ascending excursion	Excursion involving reduction in ambient pressure
Bell	Diving bell. Submersible Diving Chamber (SDC)
Chamber	Used as a generic term for non-submerged pressure chambers (living chamber, transfer chamber, decompression chamber, deck decompression chamber (DDC) etc.)

Compression (phase)	Increase of chamber internal pressure either during the initial phase of a saturation dive or any later increase in storage depths.
DCS	Decompression sickness
Depth	In the context of this document used synonymous with the ambient pressure of the diver irrespective of whether exposure is immersed or dry, usually expressed in msw
Descending excursion	Excursion involving increase in ambient pressure
Excursion	Vertical movement of the diver in the water column or change of pressure in the diving bell
Excursion range	The allowed change in pressure variation during an excursion, usually expressed in msw, relative to storage
Excursion window	See excursion range
Helix	Helix Well Ops, diving contractor
HPNS	High Pressure Nervous Syndrome
Intermediate compression	Increase of chamber pressure between two storage depths
Intermediate decompression	Decrease of chamber pressure between two storage depths
mbar	Millibar
Mixed excursion	Excursion involving pressure increase and decrease relative to storage depth
msw	Meters of seawater. Used in this document to express ambient pressure irrespective of whether exposure is immersed or dry.
MT92	French decompression tables[3]
NCS	Norwegian Continental Shelf
NDA	Non-disclosure agreement
NORMAM15	Brazilian diving regulations[4]
NORSOK	In this document used as an abbreviation for Norwegian standard for manned underwater operations, NORSOK U-100:2015[1]
pAr	Partial pressure of argon
pCO_2	Partial pressure of carbon dioxide
pN_2	Partial pressure of nitrogen
pO_2	Partial pressure of oxygen
PSA	Petroleum Safety Authority Norway
S7	Subsea 7, diving contractor
Storage	The period of a saturation dive when pressure of the chamber is held practically constant inbetween periods with wet diving, bellruns and/or excursions.
Surface	Term used to describe ambient pressure at surface
TFMC	Technip FMC, diving contractor
USN	US Navy. Will in this document even be used for the publication US Navy Diving Manual[5]
VGE	Venous gas embolism (usually asymptomatic free gas in venous blood measured with ultrasound)
W profile	In this document used to describe a pressure profile with an intermediate decompression followed by an intermediate recompression

The divers are exposed to increased ambient pressure during the saturation. This pressure, and pressure variations, should be expressed in kPa or MPa to comply with the appropriate SI unit. However, industrial practice has established “meters of seawater” (msw) and “feet of seawater” (fsw) as the commonly used pressure unit in verbal, as well as written communication. We will therefore use “depth” and the pressure unit msw irrespectively of whether the diver is exposed to pressure in the dry or immersed. Similarly partial pressures of oxygen, nitrogen and carbon dioxide are by convention listed in mbar in the majority of the procedures and we will retain the use of bar for such purpose. We have converted units according to that cited in US Navy Diving Manual Rev 7[5]: 10 msw = 32.6336 fsw = 1 bar = 100 kPa.

4 Methods

When this project was started it was recognized that another group of scientists was working on a closely related subject: Characterizing commercial saturation diving procedures. The other group focused initially on the saturation decompression procedures. The authors of the present report invited the colleagues for a collaboration on this study, but it was not possible to establish this within the time constraints established by the client of this work. PSA requested a report to be issued within 2023-11-01, i.e. approximately 6 months after project start.

Based on the time constraints (described above) it was agreed to focus on procedures accessible from diving contractors working on the Norwegian continental shelf (NCS) and secondary those working on the UK continental shelf.

Elaboration and negotiations of non-disclosure agreements (NDAs) with diving contractors on the NCS took place June-July 2023 and a final agreement with both contractors reached August 2023. At that time two contractors working on the UK continental shelf had been contacted. One of these agreed to share information, while the other declined. The diving contractors sharing their saturation diving manuals under NDA’s were:

- Helix Well Ops (Helix)
- Subsea 7 (S7)
- Technip FMC (TFMC)

The saturation diving manuals were shared with the authors under an NDA. The NDAs were adjusted according to requirements from the contractors, but all of them held these limitations:

- The contents of the manuals should not be shared or distributed for anyone but the authors.
- The data retrieved from the diving manuals should be de-identified.
- The diving contractors should be given the possibility to read and comment on the final report, but the responsibility for the contents of the report would be that of the authors.
- The diving contractors would have the right, at all times, to retract the consent to use and present the data from the diving manuals until the final report had been released in public.

Diving manuals were received June-July 2023. Data was collected from these in an iterative process. A number of parameters had been identified a priori such as compression rates, pO_2, pN_2, pCO_2, relative humidity (RH), temperature, excursion windows (see below), hold and stabilization times. When the manuals were scrutinized it was noted that some of the procedures identified criteria related to excursions after intermediate decompression and such parameters were added to the analysis.

We have completed a non-systematic search for public regulations, standards and procedures describing detail of heliox saturation diving to depths in the range 0-250 msw. This was done based on the authors’ previous knowledge, a request to the diving manager of the three diving contractors on their awareness of such standards and a review of a report detailing national regulations related to oil and gas exploration[6]. No additional standards were identified after approach to IMCA Diving Committee chair (Steve Sheppard) and TFMC (Andy Butler) and Subsea 7(John Duncan), personal communication, September/October 2023). The public standards and procedures retrieved for comparison were:

- Brazilian diving regulations (NORMAM15)[4]
- French diving regulations (MT92)[3]
- Norwegian standard for manned underwater operations (NORSOK)[1]
- US Navy Diving Manual (USN)[5]

The US Navy Diving Manual and the manuals received from the diving contractors hold detailed procedures related to the saturation exposure. In contrast MT92, NORMAM15 and NORSOK list selected limitations and threshold values not to be exceeded. These three documents can't be used as operational procedures but need to be implemented in the diving contractor's diving manual. We will use the generic term "procedure" when we discuss diving manuals and standards in general unless a specific document is referred to.

5 Results

The most important findings will be presented in the text below. The reader is adviced to review Tables 1-8 and Figures 1-4 for detailed results.

5.1 Compression phase

Findings are presented in Tables 1-3, Figure 4 and Figure 5. Most of the procedures define threshold values for atmospheric composition (Table 1 and Table 2) in addition to compression rates and hold times. USN allows a slightly higher pO_2 during compression and bottom phase than the other procedures. NORSOK advice for a pO_2 to be adjusted as close as possible to 210 mbar.

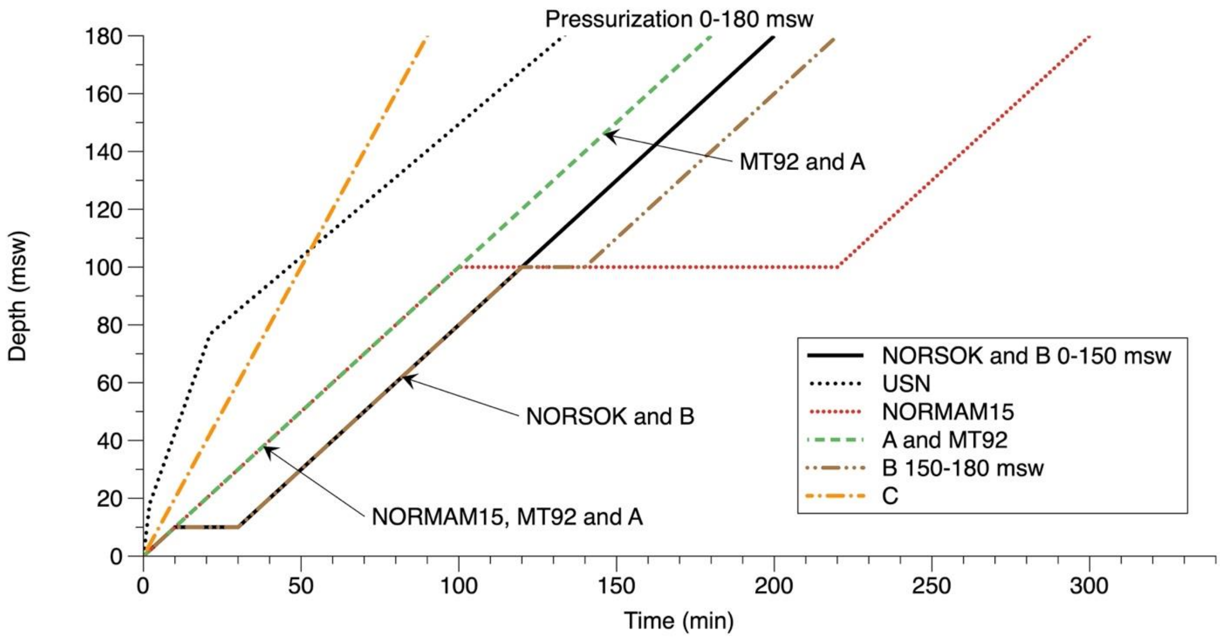

Figure 4 Compression time to 180 msw for three offshore diving contractors, USN and three public standards and regulations. For abbreviations see text. Most diving procedures advice for additional system checks at 3-4 and/or 10 msw, but these have not been included unless stop time has been defined in the procedures. NORMAM15 and Contractor A have superimposed compression rates to 100 msw. Similarly NORSOK and contractor B procedures are superimposed to 150 msw.

Contractor C and USN allows faster compression rates than the other procedures, while NORMAM15 has consistently slower compression rates than all others (Figure 4and Figure 5, Table 1 and Table 3). NORSOK specifies a 20 min stop at 10 msw, except for this fact Contractor A, Contractor B, NORSOK and MT92 compression rates are identical down to 150 msw and with only minor differences to 180 msw. There are only three procedures listing compression rates to depths exceeding 200 msw: Contractor B, NORMAM15 and USN. USN allows significantly shorter compression time to depths ranging 180-250 msw than the other two procedures.

As shown in Figure 4 and Figure 5 there are differences in hold times during the compression phase. NORSOK and company B call for a fixed 20 min hold at 10 msw while the other procedures call for safety stop at this depth without stipulating time. Contractor B and NORMAM15 have identical compression rates to depths ranging 225-250 msw. Two procedures call for a hold at 100 msw: NORMAM15 for 2 h and contractor B for 20 min if first storage depth exceeds 150 msw (Table 1). For saturations exceeding 180-200 msw NORMAM15, contractor A and contractor B require an additional 2 h hold at either 100, 180 or 200 msw (see Figure 5 and Table 1 for details). The differences in compression rates increase when first storage depth exceeds 180 msw (see Figure 5).

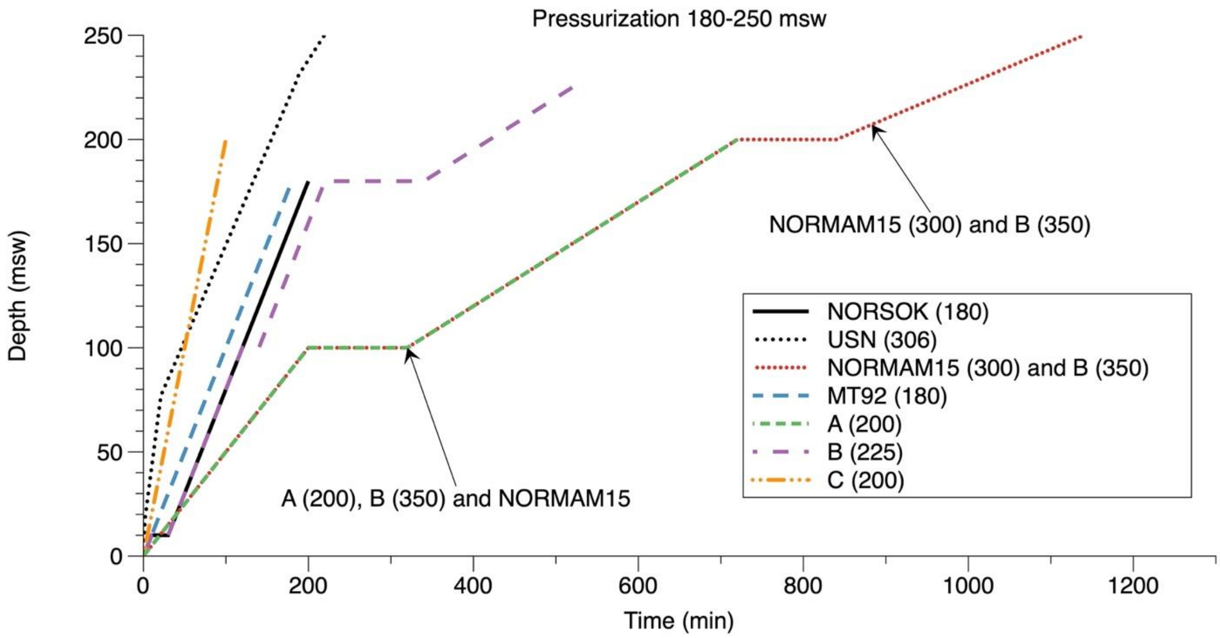

Figure 5 Compression time to 250 msw for three offshore diving contractors, USN and three public standards and regulations. For abbreviations see text. Most diving procedures advise for additional system checks at 3-4 and/or 10 msw, but these have not been included unless stop time has been defined in the procedures. The numbers in brackets indicate the maximum depth allowed for the specific procedures. The NORMAM15 and Contractors A and B procedures are superimposed to 200 msw, while NORMAM15 and contractor B are superimposed for depths ranging 200-250 msw..

It should be mentioned that most procedures specify that the compression rates listed in their tables are maximum compression rates not to be exceeded. The procedures advice for adjustment (in practice a slowing) compression based on the divers comfort. (E.g. from Contractor C diving manual: *Compression rate not to exceed diver comfort or 2 meters per minute.*)

5.2 Storage and excursions

Characteristics of storage (living depth) parameters and excursion ranges are presented in Tables 1-3, Figure 6-Figure 7 and Figure 9-Figure 16. .

Atmospheric physical characteristics (temperature, relative humidity, partial pressure limitations) are equal during compression and storage (Table 1 and Table 2) though some of the procedures allow pO_2 to shortly exceed threshold values immediately after finished compression.

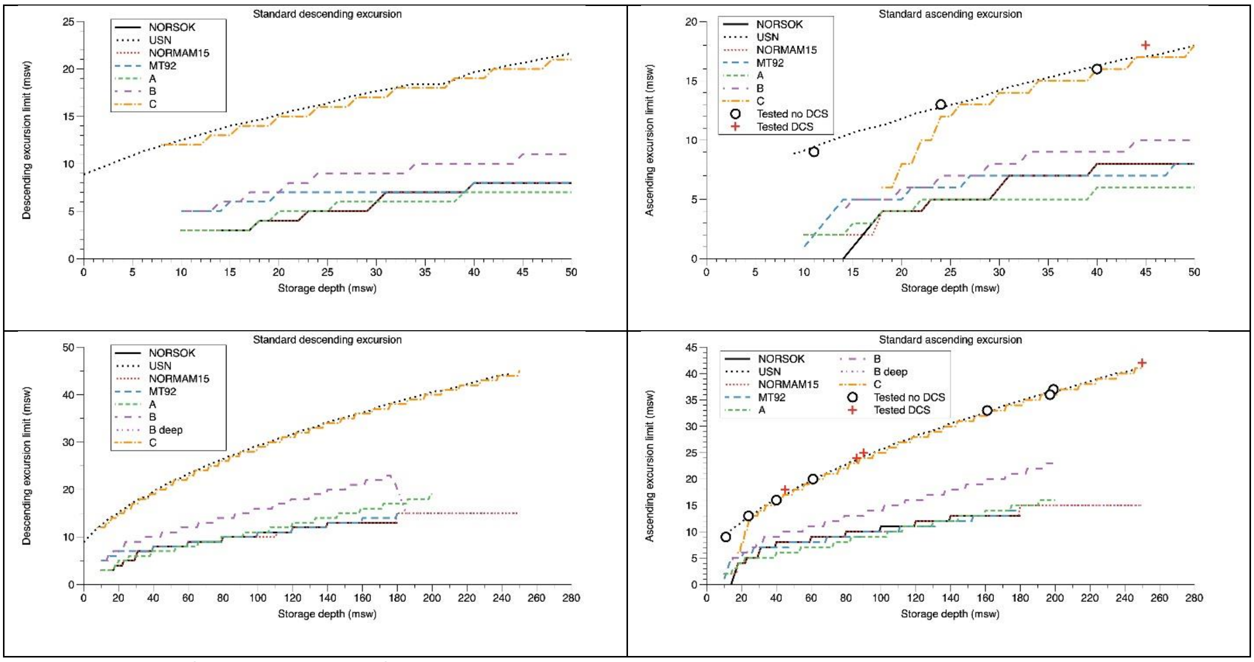

Figure 6 Ranges for descending (left) and ascending (right) standard excursions. Top row: 0-50 msw storage depth, bottom row 0-250 msw. Symbols in right column refer to excursions tested in a study reported by Thalmann[7]. See discussion for details. High-resolution figures are presented in the end of the report as Figure 9-Figure 12.

There are significant differences related to allowances and restrictions for excursions (Tables 4-8). USN requires a 48 h stabilization period before any excursion – a hold period much longer than any of the other procedures. NORSOK and contractor A advice against ascending excursions. USN and contractor C restrict the ascending excursion distance based on the deepest depth reached within 24-72 h while the other procedures allow ascending excursion distance to be decided based on storage depth or deepest depth reached the past 12 h (Table 5).

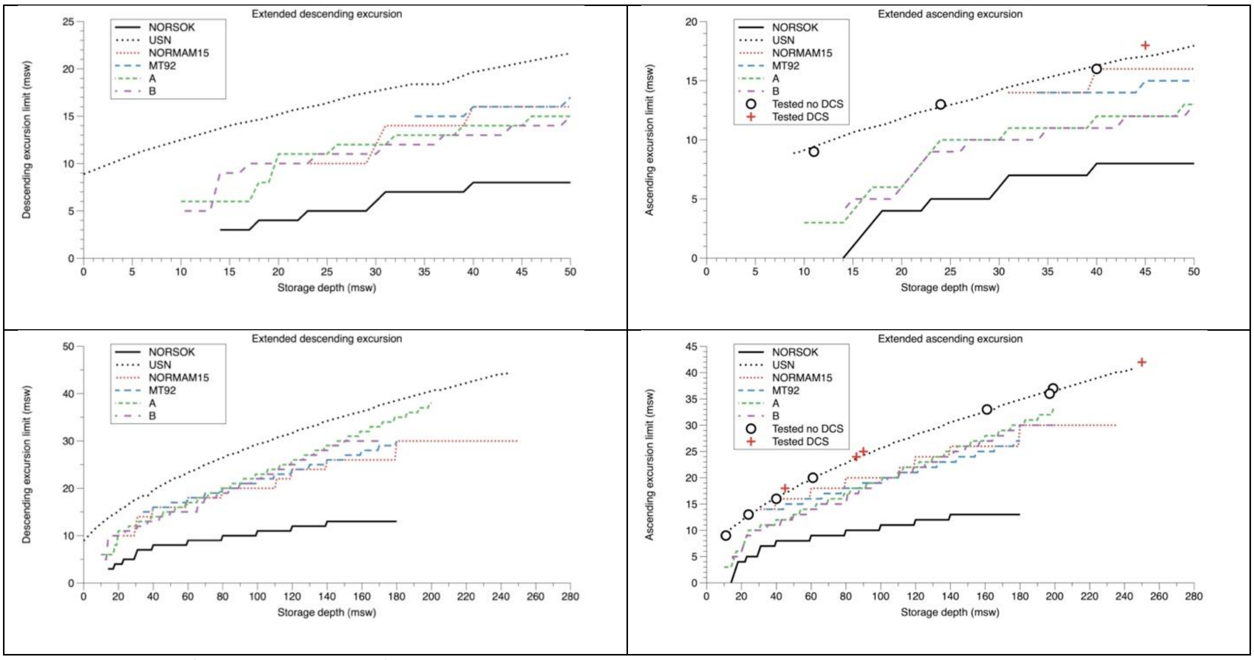

Figure 7 Ranges for descending (left) and ascending (right) extended excursions. Top row: 0-50 msw storage depth, bottom row 0-250 msw. USN, NORSOK and Contractor C have only one set of excursion ranges. See Figure 6 for Contractor C excursion ranges. Symbols in right column refer to excursions tested in a study reported by Thalmann[7]. See discussion for details. High-resolution figures are presented in the end of the report as Figure 13-Figure 16.

All but the NORSOK, USN and contractor C allow a double set of excursion ranges (Figure 7). Standard excursions are those with least restrictions on number, inter- and post-excursion hold.

Standard excursion ranges are typically 20-30% of the USN excursion windows. The extended excursions allow a greater excursion window, typically 70-90% of USN ranges, but require longer inter-excursion hold periods (Table 8). USN and contractor C have almost identical excursion limits. USN has consistently the broadest excursion ranges, but the differences between the extended excursion ranges and those of USN are relatively small. The difference between USN and the standard excursion distances of the other procedures increase with increasing storage depth. NORSOK has generally the most conservative (smallest) excursion windows, but the differences to MT92 and contractor A are of a small order.

The procedures have different ascending excursion ranges, but in addition there are different methods of calculating the ascending excursion range (Table 5). NORSOK, MT92, NORMAM15 and Company A prescribe an ascending excursion range based on current storage depth. USN, Contractors B and C prescribe an ascending excursion range dependent on the deepest depth reached the last 12-48 h. This would tend to predict stricter ascending excursions for the latter three procedures.

W-profiles, i.e. recompression to a deeper storage depth after an intermediate decompression, are allowed by contractors A and B if certain restrictions are respected. NORSOK does not allow W-profiles while USN, MT92, NORMAM15 and contractor C have not regulated use of W-profiles (Table 5).

5.3 Exposure and outcome data

Two of the companies (A and B) have shared their company-internal documents describing the development of their procedures. Both companies have a complex history as they have developed as mergers of previous diving contractors. US Navy and Comex saturation procedures formed the basis for the diving procedures for the precursors of the two companies. Excursion procedures seem to be initially adopted from the USN Diving Manual[8, 9], but later made more restrictive due to experience gained during operational use.

Contractor A describes in their “provenance document” the development of their saturation diving procedures.

Contractor B refers to seven incidents of decompression sickness type II (nausea and vertigo) after excursion dives during a 16-year period (1992-2009) in the UK sector. The excursion-related DCS incidence/man-saturation was estimated to be 0.8±0.2 %. Five of these cases were related to excursions to maximum permitted excursion distance and two cases within 80% of the maximum permitted excursion distance. The contractor adjusted in 2009 the standard excursion window to approximately 60% of the original US Navy limits[8] and significantly reduced the excursion limits for extended excursions. Contractor B has reported on average 1125 bellruns/year during 2017-2022 with two possible incidents of pain-only DCS.

Contractor C has not shared a detailed description of table development but reported on average 307 bellruns/year during 2013-2022 with no DCS incidents.

The Norwegian Petroleum Safety Authority issues an annual report[10] of petroleum-related diving activity and accidents related to diving under Norwegian legislation. The last occurrence of DCS was reported 2002. A total of 1 075 130 man-hours in saturation was reported during 2003-2020 (Jon Arne Ask, PSA Norway, Personal communication 2021).

6 Discussion

As stated in the introduction, the main objective of this study was to compare characteristics of heliox saturation compression and excursion parameters from selected diving contractors and procedures published in the open domain. We have reviewed procedures from three diving contractors and four public statutory provisions. We have disclosed significant differences between the procedures.

Evaluation of the commercial diving procedures is challenged by the paucity of published studies reporting key performance indices such as HPNS symptoms, decompression illness and divers' personal perception of health and well-being during and after the saturation periods. The US Navy published the first heliox saturation procedures in the 1973 edition of the US Navy Diving Manual[8]. They were modified in later revisions of the manual and has served as a basis for heliox saturation procedures used by many commercial diving contractors later. Two of the companies sharing their procedures in the present work have additionally shared their internal documents describing the history and justification of present procedures. These documents are not published in the open domain but explains how knowledge from experimental dives (mainly focused on HPNS) and experience gained during operational diving (compression arthralgia, HPNS, DCS) have motivated changes of compression rates, hold periods, pO_2, excursion windows and decompression rates. While these justification documents describe in generic terms the background, they list, with a few exceptions, little specific information allowing quantitative risk assessment. One exception is the Comex diving database[11] holding data from this contractor's diving activity from 1975 to 1994. For 1990 this database hold exposure data and accident/near-miss forms for 1000 saturations. This is probably the most extensive and accurate database for commercial saturations dives. However, detailed data has not been published in the open domain.

At present diving deeper than 200 msw is uncommon and the knowledge and experience with HPNS is fading. We suspect that this gradually have caused the perception that such experience is quite sparse. In this context it is worth noting that during work for PSA, Segadal[12] identified 248 saturations deeper than 300 msw and argued that it is not unlikely that actually more than 750 dives to more than 300 msw had been performed in the world at that time. It is thus likely that several thousand divers have experienced HPNS and if HPNS is likely to cause permanent sequalae it is strange that this has not been more frequently reported.

Many factors influence the final decisions of these procedures. From an operational and commercial aspect, the compression and decompression phase should be as short as possible since this time is not available for underwater work. However, a too rapid compression may cause thermal discomfort (adiabatic heat), compression arthralgia[13, 14] and HPNS[15]. A high pO_2 will allow faster decompression[16] and/or reduce DCS probability[16] but may cause pulmonary oxygen toxicity[17]. Likewise a large excursion window will allow flexible diving operation, but will increase the risk for DCS[18].

6.1 Compression rates and stabilization periods

Divers may experience joint pain during compression (compression arthralgia) and the incidence increase as a function of compression rate and diving depth[5, 14]. The review by Bradley et al.[14] as well as many studies investigating HPNS during deep saturations have reported compression related joint pain[13, 19-21]. The operational procedures reviewed in this work list maximum compression rates and advice compression rate to be adjusted according to the divers' comfort. The absence of standardized symptom scoring systems challenges comparison of studies and procedures and we have not been able to compare the procedures with respect to this outcome.

HPNS symptoms seems to increase when chamber temperature is too high[22, 23]. Adiabatic heat could contribute to temperature rise, but modern life support systems will generally be able to maintain target temperature with compression rates relevant for saturation diving. We advice chamber temperature to be adjusted according to divers' comfort.

Tremor, often a symptom of HPNS, has been reported after rapid compression to 131-152 msw, but generally a depth of 180 msw or more is required to observe clinically relevant HPNS symptoms[15]. Detailed description of HPNS symptoms and findings is beyond the scope of this report, comprehensive reviews have been published by Talpalar[24] and Bennett and Rostain[15]. Common symptoms and findings are dizziness, tremor, reduced cognitive function, sleep disturbances, EEG changes, nausea, abdominal pain and reduced appetite. Decreasing the compression rate and introducing nitrogen in the breathing gas will reduce HPNS symptoms. HPNS symptoms will gradually decrease during the bottom phase, a stabilization period in the living chamber before bellrun is commonly used to ensure that the divers are fit for work.

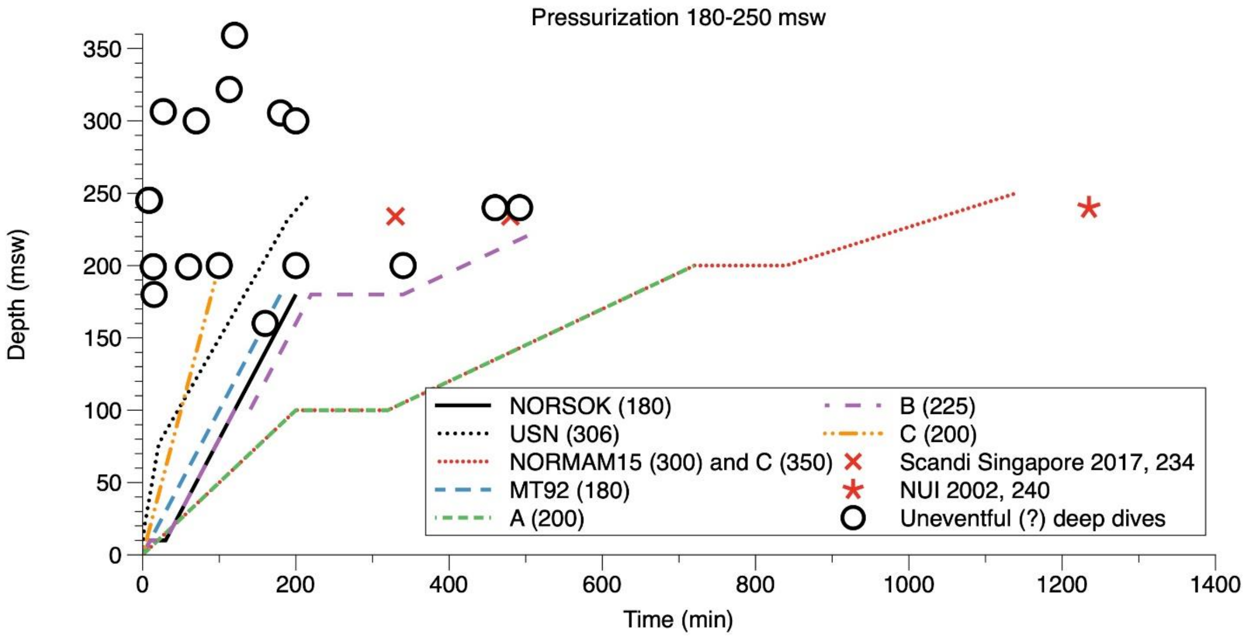

Figure 8 Summary of compression rates of some historical heliox saturation dives (symbols) compared to present recommended procedures (plots). Red symbols identify studies with subjects suffering HPNS and persistent neurological sequelae after finished saturation. Black symbols identify studies[25] with minimal or moderate HPNS symptoms but without recognized sequalae. See Discussion for further details.

As shown in Table 3 and Figure 5 there is a significant difference in compression time between the procedures. The difference ranges 3:30 (h:min) comparing NORMAM15 vs Contractor C at 180 msw and reaches 14:30 comparing USN and Contractor B for a storage depth of 250 msw. Værnes et al.[19] have previously reported severe HPNS symptoms in divers compressed in a Heliox atmosphere to 250 msw in 1:25 (approximately 3 msw/min). None of the procedures reviewed in the present study advice for a compression rate of this order. Two recent studies have investigated HPNS symptoms and findings during heliox saturation dives to depths ranging 180-300 msw. Ardestani et al.[26] examined 46 divers for HPNS during three commercial saturation dives ranging 186-207 msw. The procedures called for 5:54 compression time to 186 msw and 7:42 to 207 msw. The study included a number of psychometric tests as well as subjective symptom scoring. While 1/3 of the divers reported symptoms compatible with HPNS during each saturation and symptoms *could* last for up to five days, most divers reported symptoms for one day only. They found no relationship between subjective symptoms and psychometric measurements and no diver showed symptoms reaching a threshold of clinical HPNS. The findings suggest that 7 h of compression time is sufficient to avoid HPNS symptoms at a storage depth of 200 msw. Sun et al.[27] reported findings from a 300 msw simulated saturation dive. Compression of the four divers lasted 13 h (240 msw was reached after 8:12). Psychometric tests were applied at surface, 195 msw and after finished compression. Though there were small changes in some of the tests at depth, the performance and mental ability were virtually unaffected. During a simulated saturation dive to 360 msw HPNS symptoms were evident when 240 msw was reached after 7:40[21], but the subjects did not score symptom severity of an order incompatible with immersed diving. However, these findings strongly suggest that the maximum allowed compression rates to 240 msw and deeper in the USN procedures may cause HPNS symptoms affecting operational capacity in some divers. While slower compression rates in general will decrease HPNS incidence, it should be recognized that lengthening of compression time, without appropriate compression holds, may interrupt diurnal rhythm. The effect of sleep disruption on HPNS incidence has not been formally studied, but we would expect it to be disadvantageous.

HPNS is generally considered a fully reversible syndrome not leaving after-effects. A recent (2019) commercial saturation dive outside Australia has challenged this opinion. Information of complications have been made public through media coverage, a conference presentation[28], personal communication (Ian Millar, personal communication 2019) and a 2023 court decision. Fifteen divers participated in the 27 days exposure with storage depths of 234 and 250 msw. Maximum excursion depth was 273 msw. The first group of divers were compressed to 234 msw in approximately 8 hours. The second group of divers were compressed in 5-5.5 hours. Chamber temperature felt uncomfortably hot during compression for divers in one of the groups. Both groups were compressed at night and participated in an emergency drill with cold stress immediately after reaching storage depth. Twelve out of thirteen divers reported prolonged cognitive impairment immediately after surfacing, eleven had persistent problems three months after the saturation and seven divers remained unfit for work 28 months after the saturation. Informal discussion (verbal, internet fora etc.) commonly suggest the relatively fast compression rates to be a major cause of the neurocognitive sequelae after the saturation. However, it should be noted that none of the divers reported severe HPNS, most reported only mild HPNS. They were able to complete the diving work and did not formally report (post dive questionnaire) symptoms after surfacing. Concealing symptoms is a possible explanation, but the absence of formal reporting suggest that other factors than persisting HPNS should be considered. We will discuss this in some more detail below.

There are but a few similar case stories. Aarli et al.[29] investigated neurological symptoms and findings in 23 divers participating in four on- and offshore saturation dives to 300 and 350 msw. The divers suffered mild to moderate HPNS when depth exceeded 200 msw. Four out of these 23 divers demonstrated objective neurological changes (findings) when examined shortly after surfacing. They had reported various extent of HPNS after compression, but no symptoms suggesting DCS during or after decompression. The author suggested that HPNS may unmask clinically silent minimal brain lesions. Details of compression rates are not revealed in the report. Værnes et al.[19] reported EEG changes during a 300 msw dry simulated dive, these persisted even after surfacing. In a 250 msw saturation dive at NUI, two subjects experienced HPNS reaching 240 msw storage depth although compression lasted 20:35. pN_2 was deliberately reduced to approximately 20 kPa in the initial part of compression and maintained low during the rest of the saturation period. One of the subjects suffered persistent neurological sequelae after finished decompression[30]. The findings reported by Millar[31], Værnes et al.[19], Aarli et al.[29] and Grønning et al.[30] *might* suggest that some of the HPNS symptoms may persist as neurological sequelae in exceptional cases, however we would caution against firm conclusions based on the paucity of data. The exact time for compression to 237 msw reported by Millar[31] has not been confirmed by other sources, but the compression time of 5-8 hours is not of an order shorter than a number of other simulated dives to the same depth[21, 27, 32, 33] (Figure 5). If this compression time is correct it suggest, similar to the findings of Grønning et al.[30] that other factors than compression rate may contribute to HPNS symptoms and possible neurological sequelae. The nature of these factors could be pre-existent subclinical brain injury (individual vulnerability), chamber/breathing gas impurities (e.g. volatile organic compounds, carbon monoxide), thermal stress, sleep disruptors, low pN_2 or others. Indeed a review of previous Norwegian saturation dives concluded that diving depth was a predictor for development of neurological sequelae after deep dives[34]. It is premature to suggest a causal relationship between compression rates and persistent neurocognitive sequelae after deep saturation dives.

6.2 Excursion procedures

The safety of excursion ranges (excursion windows) has traditionally been assessed based on the likelihood of provoking DCS. The last reported incidence of DCS related to saturation diving complying with Norwegian regulations was reported in 2002[10]. DSYS reports from PSA[10] as well as experience from Contractors B and C suggest that DCS is such a rare incidence in modern saturation diving that it is impossible to compare excursion procedures using reported DCS as an outcome variable.

A previous study by Spaur et al.[18] reported findings from 11 experimental heliox saturation dives with 245 man-excursions. This study included repetitive ascending as well as descending excursions. The excursion tables were published in the 1977 USN Diving Manual but were modified in 1980 with more restricted excursion windows. According to Thalmann[7] this modification was motivated by a disturbing DCS incidences experienced in the USN. Thalmann[7] reported DCS outcome after 18 upward excursions (164 man-excursions) from storage depths ranging 2-306 msw (6-1000 fsw). No case of DCS occurred within the first 8 h after finished excursion and the author concluded that the new USN excursion tables would be safe. This conclusion holds a strong internal validity but should be interpreted with caution when applied to current commercial saturation diving. The experiments were done with divers stabilized for 48 h before the ascending excursion took place and the excursion was immediately followed with a saturation decompression. These factors were thus adjusted to a “worst case” scenario. However, no descending, mixed or repetitive excursions were tested. This contrasts to the reality of current operational saturation diving. Excursions practiced in operational diving may theoretically induce asymptomatic bubbles that may amplify and possibly cause symptoms during succeeding decompression. Indeed, the DCS reported by Thalmann[7] appeared 8h or longer after finished excursion. However, there are reasons to suggest that Norwegian[1], French[3] and Brazilian[4] excursion limits imposed on shallow saturation diving are unnecessary narrow. NORSOK U-100:2015[1] does not allow any ascending excursions from 14 msw storage and limits downward excursions to 3 msw from this storage depth. Thalmann[7] reports three ascending man-excursions from 11 to 1.5 msw without DCS. He cites earlier work (published as internal reports) concluding that the threshold storage depth for developing symptoms after surface ascent from heliox saturation dives were in the order of 11 to 15 msw. Only two out of eight subjects had venous gas embolism (VGE) following surface ascent after a 5 msw (150 kPa) simulated saturation dive at NUI in 1995 (Segadal and Risberg, personal communication 2023). A narrow excursion limit will protect against DCS, but this risk should be balanced against any safety concerns related to positioning the diving bell too close to the divers’ worksite. Two simulated dry dives with saturation at 100 msw were conducted at NUI in 1998 and 2000. After sixteen man-excursions from 111 to 100 msw no bubbles were registered with ultrasound and only one occurrence of grade 1 bubbles was registered after sixteen man-excursions from 48 to 40 msw (Kåre Segadal, personal communication 2023). These ascending excursions were compliant with the threshold limits of the NORSOK standard[1].

Valerie Flook developed a mathematical model predicting volume of gas in the pulmonary artery and brain after decompression in man. Her model was calibrated to measurements of venous gas embolism. She reported[35] predicted volumes of pulmonary artery and brain free gas after excursions and during decompression from heliox saturation dives. The model was applied to a dataset of nine ascending and nineteen descending excursions from six storage depths ranging 30-180 msw. The selected excursions included the maximum excursions allowed by contractor C (which are almost identical to USN) for each of the six storage depths. In addition, two or three descending excursions of less magnitude were tested for each storage depth. The model predicted less free pulmonary artery gas after single upward and downward excursions than what could be expected to be measured with ultrasound and far less than that predicted to be required to cause DCS. Ascent rates (18, 10 and 5 msw/min were tested) had little effect on estimated pulmonary artery gas volume, but somewhat more effect on estimated brain gas volume. Probably more relevant was the effect of hold periods on estimated bubble volumes. Extending hold times from 6 to 12 h had a great impact on the volume of gas remaining after excursions. This effect was even more pronounced when the excursion was followed by a decompression. For dives with large excursions, extension of the pre-decompression hold would significantly reduce the amplification of gas bubbles taking place during decompression. To cite from the work: *The main conclusion from the work is that neither the excursions currently used nor the decompression procedures are likely to cause decompression problems. The risks* *result from the combination of excursions followed by decompression before bubbles have totally resolved. Starting decompression whilst bubbles are present is the single significant factor.* The 5-6 h post-excursion hold periods in present commercial heliox diving procedures is most likely sufficient for "standard" excursion windows, but it would be wise to consider longer hold periods for excursions closer to the original USN unlimited excursion ranges.

NORSOK U-100:2015[1] clearly states that *It is of special importance to restrict the use and distance of upward excursion.* The origin of this statement is unknown. It was not printed in the original report[2] that founded the basis for the excursion limits. Contractor A states in their diving procedures: *Upward excursions carry a higher risk of decompression illness than downward excursions…* The French regulations[3] states (author's translation): *For a given dive, we will preferably choose descending excursions rather than ascending*. The statement is not justified further. The other procedures and standards reviewed in this work don't provide similar guidance. We speculate whether this perception has been based on personal opinion rather than findings from experimental or epidemiological studies. Lambertsen[36] stated in 1972: *With effective decompression tables for the depths involved, it is a highly practical procedure to carry out deeper excursion diving from a saturation depth. It is not practical to carry out excursions to shallower than saturation depths since bubble formation and development of decompression sickness is inevitable if the ascent is greater than approximately 20 feet of sea water above the saturation level.* Brubakk et al.[37] reported the observation of arterial bubbles after 50 msw ascending excursions from 300 msw during a Norwegian simulated saturation dive[37] in 1986, only four years before the Norwegian Petroleum Directorate initiated the work to review frame conditions for heliox saturation diving[2]. We have not identified other scientific reports addressing a specific concern related to ascending excursions. It seems plausible to assume that a descending excursion will create bubbles when the diver returns to storage and that these bubbles will gradually disappear during the inter-excursion storage period. In contrast the ascending excursion will create bubbles at the immediate start and then gradually disappear during the excursion and be further eliminated when the diver is recompressed to storage. Since DCS after excursions is an extremely infrequent event, most concern should be related to the possibility of free gas existing at the time of final or intermediate decompression. Such gas would be expected to expand unless compensated with a low decompression rate and/or high decompression pO_2. Jacobsen et al.[38] investigated 22 cases of DCS occurring during heliox saturation diving and compared these to two randomly selected uneventful saturations. They concluded that the pressure differential between storage depths during intermediate decompressions was significantly larger for divers with DCS compared to divers not having suffered DCS. The study supports a theory of bubble amplification during decompression and the importance of repetitive excursions at a shallower intermediate storage depth. While measurements of VGE during and after operational saturation dives have been reported in a few studies[39-41], there is to the best of our knowledge no study directly comparing VGE after identical ascending and descending excursions. The works of Flook[35, 42] does not support the presumption of avoidance of ascending excursions. In contrast the works suggest that most bubbles created during an ascending excursion will disappear upon return to storage level. Minimal VGE was produced after ascending excursions from 3,5 and 110 msw during simulated heliox saturation dives at NUI (Kåre Segadal, personal communication 2023). In conclusion it is the opinion of the authors of this work that the advice of avoiding ascending excursions is not substantiated by published studies. We can't exclude that operational experience has justified the presumption of avoidance of ascending excursion, but if so this experience lacks formal and public documentation.

6.3 Long term health effects of diving

Diving may cause long term health effects[43]. This review, focusing on relevant operational saturation procedures, have not disclosed deficiencies in compression procedures or excursion procedures likely to cause long-term health effects. However, we must make reservations to factors outside the scope of this review. We have neither reviewed decompression procedures nor atmospheric monitoring or control systems (e.g. measurement of gas contaminants such as carbon monoxoide and volatile organic compounds or the use of adsorbents and catalysts in the atmosphere regeneration system). Inappropriate decompression procedures and breathing gas contaminants are both known to have a deleterious effect on CNS function. A previous report has suggested a positive association between diving depth and new neurological symptoms or findings after the dive [34]. We have not reviewed the potential interaction between diving depth and factors known to impact divers' health. It is possible that adaptation through exposure (allow the divers to gradually be exposed to saturation dives of exceeding depth) or selection (impose stricter selection criteria for divers participating in deep dives) may have a protective health effect. This has been implemented in NORMAM15[4] which stipulates exposure requirements for divers participating in dives deeper than 300 msw. In conclusion it is our opinion that there is no reason to expect that compression and excursion procedures, as reviewed in this document, by itself would have a negative impact on divers' long-term health.

7 References

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8 Appendix A – Tables

	Compression rate msw/min	pO_2 mbar	Compression break Time(min)@depth (msw)
NORSOK	0-180 msw: 1	As close as possible to 210 (200-1500)	20 min@10 msw
USN	0-18 msw: 9.2 18-77 msw: 3.1 77-230 msw: 0.9 230-306 msw: 0.6	446-486	NS$
MT92 0-100	3	300-450	NS
MT92 100-180	1	300-450	NS
NORMAM15 0-180	1	NS	2 h@100 msw
NORMAM15 180-300	0-100 msw: 0.5 100-200 msw: 0.25 200-300: 0.16	NS	2 h@100 msw 2 h@200 msw
A 0-180	1	400-420	NS$
A 181-200	0-100 msw: 0.5 100-200 msw: 0.25	400-420	2 h@100 msw
B 0-180	0-3 msw: 3 3-180 msw: 1	400±20*	20 min@10 msw 20 min@100 msw if storage>150 msw
B 181-225	0-3 msw: 3 3-180 msw: 1 180-225 msw: 0.25	380±20*	20 min@10 msw 20 min@100 msw 120 min@180 msw
B 226-350	0-3 msw: 3 3-10 msw: 1 10-100 msw: 0.5 100-200 msw: 0.25 200-300 msw: 0.167 300-350 msw: 0.125	380±20*	20 min@10 msw 120 min@100 msw 120 min@200 msw 120 min@300 msw
C	0-200 msw: 2	400 ±30	NS$

*Table 1 Metrics of heliox saturation compression procedures. NS: Not stipulated †: Maximum compression rate listed. Most procedures advice for adjustment dependent on divers' comfort. *: Increased pO_2 acceptable immediately after finished compression Contractor B: Max 600 mbar for dives <180 msw should be strived for but overshoot will be accepted. For dives >180 msw maximum pO2<570 mbar. $: System checks – typically at a few msw and/or at 10 msw recommended but no provision on minimum hold time.*

	RH %	Temp ºC	pCO_2 mbar	pN_2 mbar
NORSOK	40-60	Adjustable within 22-33	10 (<15 min: 30)	1500 (Ceiling: 3500)
USN	NS	In-water: -3.1 – 25.4 (depth dependent) Chamber that thermal comfort may call for : 29-34	50	NS
MT92	60-100	NS	10	NS
NORMAM15	NS	NS	NS	NS
A	40-60 (Deeper diving 40-50)	In-water:18-27 (depth dependent) Chamber: Divers comfort 22-33	5 (<15 min: 15)	800 (chamber and reclaim)
B 0-180 msw	40-60	Divers comfort: 22-31	10 (recommended max 5) (<15 min: 30)	pN_2: 1500 (DC 800) (Ceiling 3500) pAr: 500 (DC 10) (Ceiling 1500) pAr+pN_2: (ceiling 3500)
B 180- 350 msw	40-65	Divers comfort: (28-32 from 200-350 msw)	10 (recommended max 5) (<15 min: 30)	1500 (<15 min: 3500)
C	50-75	Chamber: Divers comfort (27-30) Bell: Divers comfort	Chamber: 0-5 (max 10) Bell: 0-10 (max 20)	1000

Table 2 Atmospheric threshold values for chamber and bell if not stated otherwise. NORSOK additionally stipulates pAr not to exceed 500 mbar. USN doesn't stipulate a pN_2 but allows initial compression with air to 36 fsw suggesting a pN_2 may reach approximately 1700 mbar.

	60 msw	120 msw	180 msw	200 msw	225 msw	250 msw
NORSOK	1:20	2:20	3:20			
USN	0:16	1:08	2:13	2:35	3:02	3:40
MT92	0:20	2:00	3:00			
NORMAM15	1:00	2:00	5:00	12:00	16:30	19:00
A	1:00	2:00	3:00	12:00		
B	1:20	2:20	3:40	7:00	8:40	19:10
C	0:30	1:00	1:30	1:40		

Table 3 Time to reach different depths for ten different heliox saturation procedures. Stabilization periods at 3 and 10 msw excluded except for NORSOK 10 msw stabilization.

	Stabilisation period after compression before diving (h)	Bell pO_2 mbar	Lockout gas pO_2 mbar	Excursion pressure rate change msw/min
NORSOK	0-89 msw: 1 90-180 msw: 2	NS	NS	10*
USN	NS	446-486	405-608	18*
MT92 0-100	NS	NS	NS	B+D: 10
MT92 100-180	NS	NS	NS	B+D: 10
NORMAM15 0-180	0-89 msw: 1 90-180 msw: 2	NS	NS	10
NORMAM15 180-300	181-240 msw: 6 240-300 msw: 12	NS	NS	10
A 0-180	0-89 msw: 1 90-180 msw: 2	350-700	500-900	B+D: 9
A 181-200	181-200 msw: 6	350-700	500-900	B+D: 10
B 0-180	0-89 msw: 1§ 90-180 msw: 2	400-800	700 (600-800)	D:10
B 181-225	181-200 msw: 4 201-225 msw: 6	400-800	700 (600-800)	NS
B 226-350	12	400-800	700 (600-800)	NS
C	1	600 (400-800)	700 (600-800)	B: 5 D: 10*

*Table 4 Excursion parameters. NS: Not stipulated B: Bell. D: Diver lockout. *: Ascent rate only. §: 2 h hold if ascending excursion*

	Ascending excursion distance calculated based on	Hold time (h) before bellrun after intermediate decompression	Hold time (h) after excursion before final or intermediate decompression	W profile allowed (intermediate decompressions/ compressions)
NORSOK	St	NS (but 12 h continuous rest per 24 h)	8	No
USN	Deepest depth reached past 48 h	NS	0 (2 h if ascending excursion from storage >61 msw)	NS
MT92	St	Standard descending: 0 Any upward or extended (maximum) descending: 12	Standard excursion: 0 Extended excursion: 12	NS
NORMAM15	St	Upward: Time needed to reach the target depth if a standard decompression rate was held	0	NS
A	St	Downward: 2 Upward <=5 msw: 2 Upward > 5 msw: 6	Before a final decompression Standard: 8 Maximum: 12	One recompression with total decompression amplitude >1.5x storage or sawtooth with total decompression amplitude <=1.5 storage
B: 0-180 msw	Deepest depth reached within 12 h	Downward: 0 Upward: Time needed to reach the target depth if a standard decompression rate was held	8	Yes, but maximum allowable decompression of 180 msw in a 28 day saturation period
B: 181-350 msw	Deepest depth reached within 12 h	Downward: 0 Upward: 12	8	Yes if new storage depth is is within the excursion depth of initial storage. Only one recompression per saturation period
C	Deepest depth reached within: 24 h: For depths <70 msw 48 h: For depths 70-197 msw 72h: For depths 198-305 msw Otherwise storage depth	Downward excursion: 0 if <50% of standard excursion distance unless hold period (see below) is respected. Ascending excursion calls for hold periods: Deepest storage <70 msw: 24 Deepest storage 70-197 msw: 48 Deepest storage 198-305 msw: 72	6	NS

Table 5 Excursion parameters. NS: Not stipulated. St: Storage depth. USN and NORMAM 15 allow saturation decompression to be initiated with an ascending excursion. NORMAM15 require stabilization period as per Table 4 to allow decompression to start with an initial ascending excursion.

	Allowance for ascending excursions following a descending excursion	Other restrictions on intermediate decompressions	Maximum bell run time (h)/24 h	Maximum divers lock out time (h)	Daily rest time (h)
NORSOK	NS		8 6 if depth >180 msw	4* 3 per 12 h if depth >180 msw	12
USN	Yes	48 h hold before new excursion	NS	(4 h recommended)	NS
MT92	Not recommended	Hold period 12 h before ascending excursion. No hold period if descending excursion	NS	NS	NS
NORMAM15	No	Time needed to reach the target depth of the ascending excursion if a standard decompression rate was held. No hold period if descending excursion	8	<210 msw: 6 211-260: 5 261-300: 4	NS
A	Yes	24 h stabilisation time required after last bellrun if time at intermediate storage is <72 h	8	0-180: 4* 181-200: 3	12
B	Yes	Not to exceed 180 msw If deepest storage >180 msw hold period 12 h before ascending excursion. No hold period if descending excursion	<= 225 msw: 8 >225 msw: 6	201-204 msw: 6 2041-260: 5 261-350: 4	12
C	No$	Unless stabilized for 24/48/72 h: No ascending excursions Descending excursions to be <50% of tabulated	8	6	12

*Table 6 Excursion parameters. NS: Not stipulated *: 6 h if certain requirements are met. NORSOK advice to restrict the use and distance of ascending excursions. $: The diving manual describe how the ascending excursion distance should be calculated in the event that an ascending excursion unplanned takes place after a descending excursion.*

	Excursion window for a mixed excursion based on	Minimum storage depth allowing any excursion msw	Minimum excursion depth msw	Maximum excursion depth msw	Advice to avoid ascending excursions
NORSOK	Not defined	14	14	193	Yes
USN	Depth of downward excursion unless deeper depth reached last 48 h	0	0	306	No
MT92	Not defined	10	9	210	No – but descending should be preferred when possible
NORMAM15	Storage depth	10	8	300	No
A	Storage depth	14	8	200	Yes
B 0-200 msw	Depth of downward excursion unless deeper depth reached last 12 h	14	10	200	No
B >200 msw	(As for 0-200 msw)			350	No
C	Depth of downward excursion unless deeper depth reached last 48 h	8	12	305	No

Table 7 Excursion variables. NS: Not stipulated

Stabilization period (h)	After a standard descending excursion	After a standard ascending excursion	After an exceptional descending excursion	After an exceptional ascending excursion
Before a standard descending excursion	MT92: 0 NORMAM15: 0 A: 12 B: 12 C: 0	MT92: 0 NORMAM15: 0 A: 15* B: 12 C: 0	MT92: 12 NORMAM15: 0 A: 15* B: 16 C: N/A	MT92: 12 NORMAM15: 12 A: 15-24** B: 16 C: N/A
Before a standard ascending excursion	MT92: 0 NORMAM15: 0 A: 12 B: 12 C: 0	MT92: 0 NORMAM15: 0 A: 15* B: 12 C: 0	MT92: 12 NORMAM15: 12 A: 15* B: 16 C: N/A	MT92: 12 NORMAM15: 12 A: 15-24** B: 16 C: N/A
Before an exceptional descending excursion	MT92: 0 NORMAM15: 0 A: 12 B: 12 C: N/A	MT92: 0 NORMAM15: 0 A: 15* B: 12 C: N/A	MT92: 12 NORMAM15: 48 A: 15* B: 16 C: N/A	MT92: 12 NORMAM15: 48 A: 15-24** B: 16 C: N/A
Before an exceptional ascending excursion	MT92: 0 NORMAM15: 12 A: 12 B: N/A C: N/A	MT92: 0 NORMAM15: 0 A: 15* B: 12 C: N/A	MT92: 12 NORMAM15: 48 A: 15* B: 16 C: N/A	MT92: 12 NORMAM15: 48 A: 15-24** B: 16 C: N/A

*Table 8 Stabilization period before a new excursion depending on the characteristics of the preceding excursion. NORSOK and USN don't stipulate hold times between excursions but NORMAM and NORSOK calls for a minimum of 12h rest between bell runs. *: 18 h if storage 172-200 msw. **: Stabilisation period dependent on storage depth: 10-22 msw: 15h, 22-124: 18 h 124-172: 24 h and 172-200 msw: 24 h. Contractor B requires a 12 h hold between excursions for diving >180 msw.*

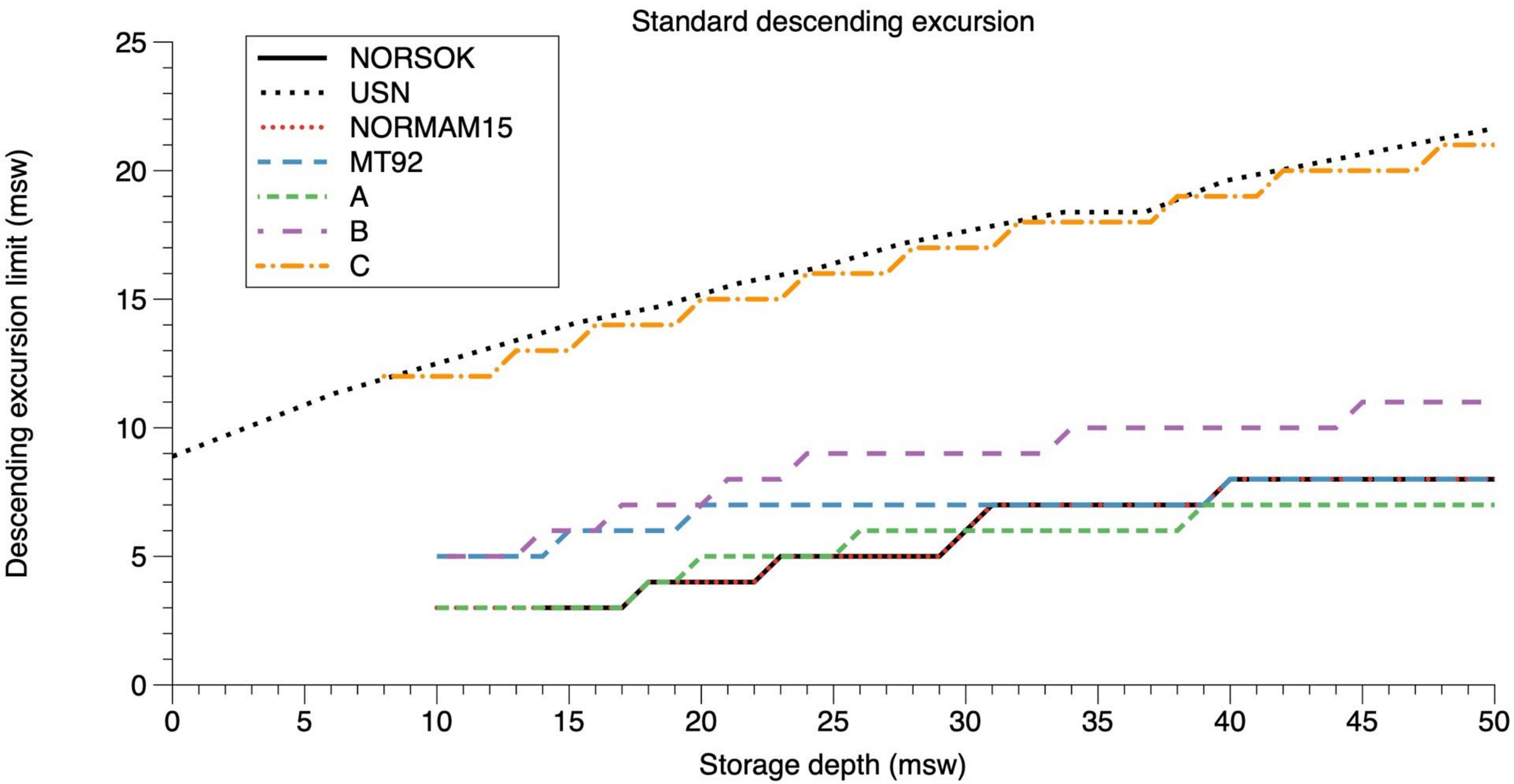

Figure 9 Standard descending excursion range for storage depth not exceeding 50 msw.

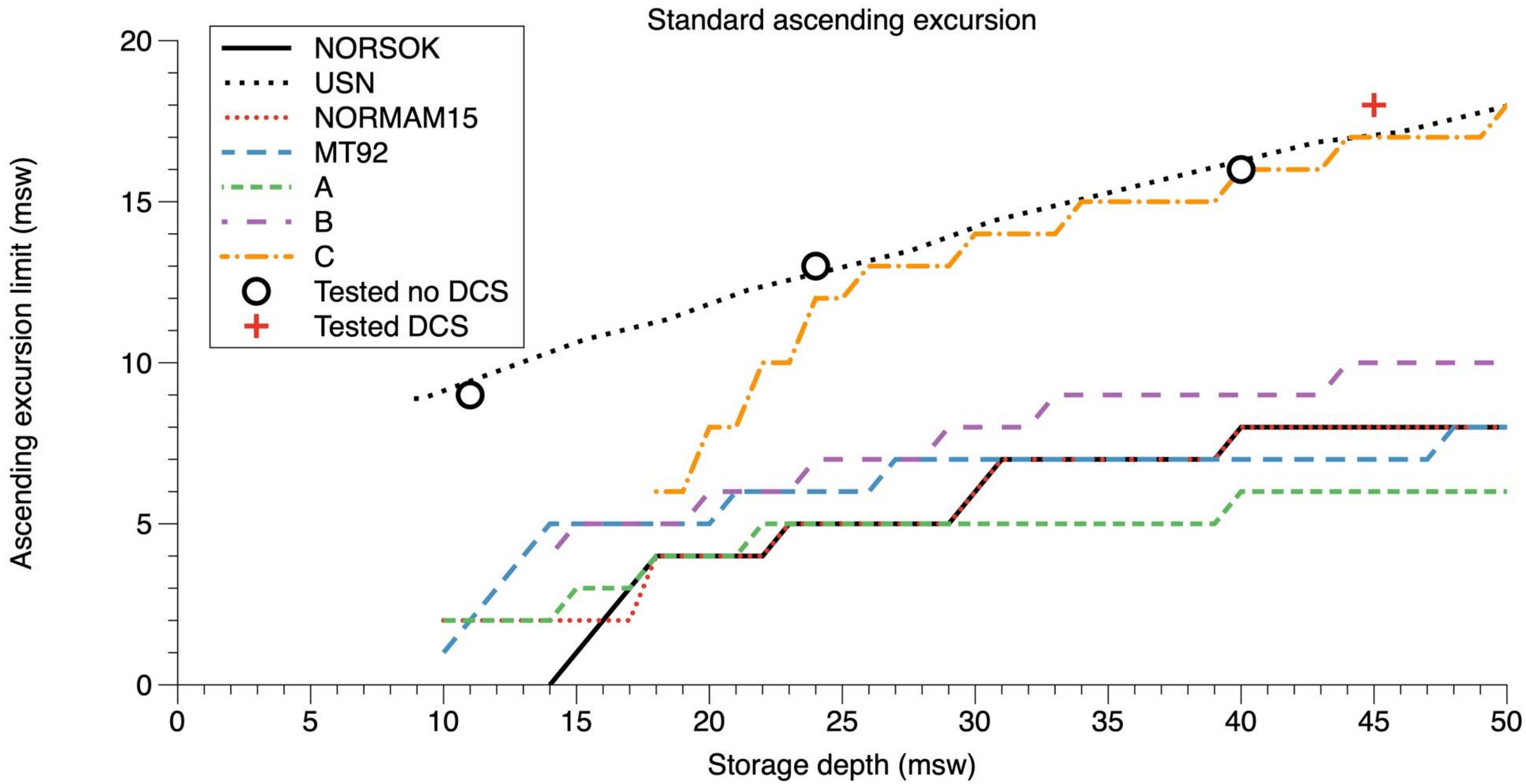

Figure 10 Standard ascending excursion range for storage depth not exceeding 50 msw. Symbols indicate excursions tested experimentally[1].

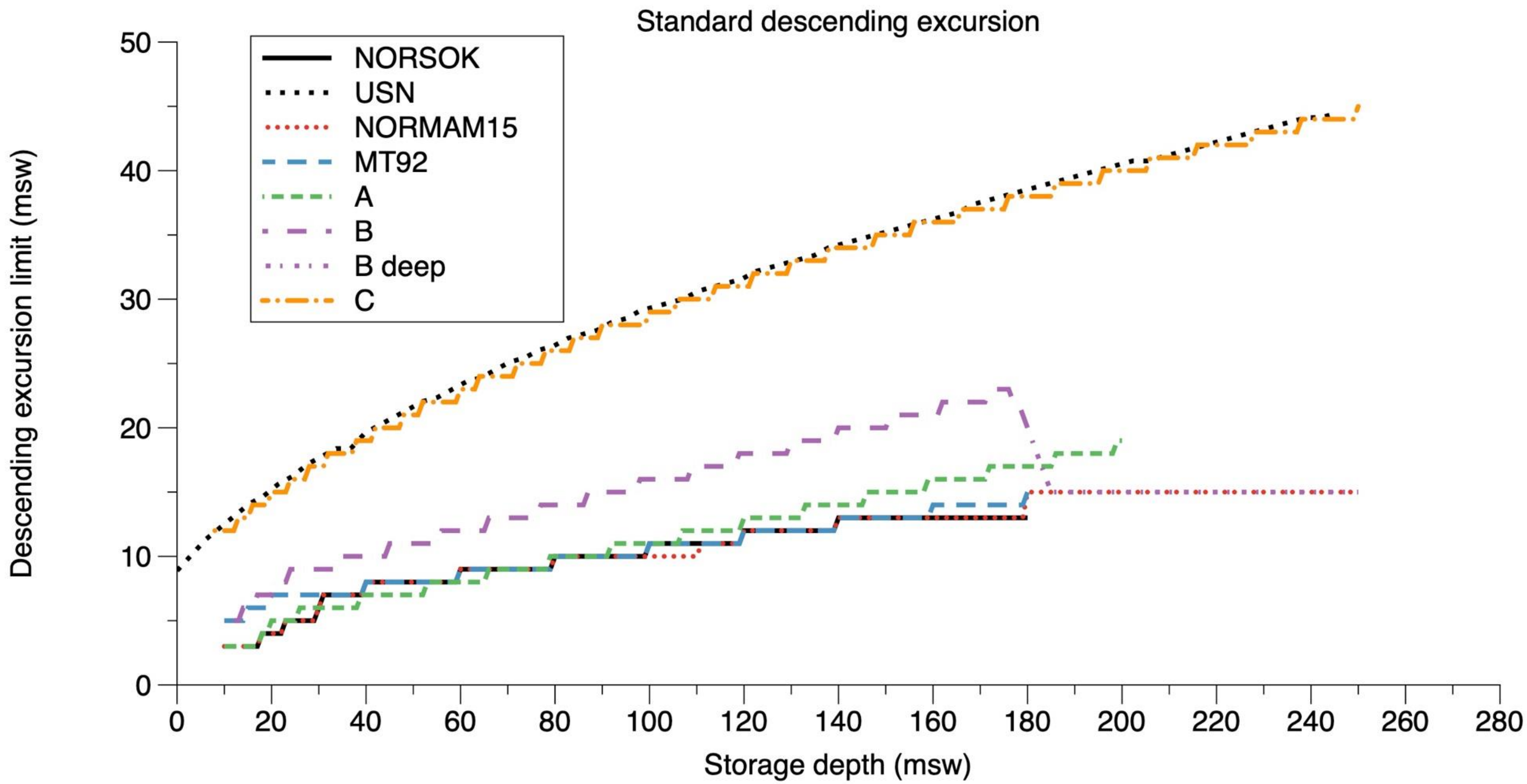

Figure 11 Standard descending excursion range for storage depth not exceeding 250 msw.

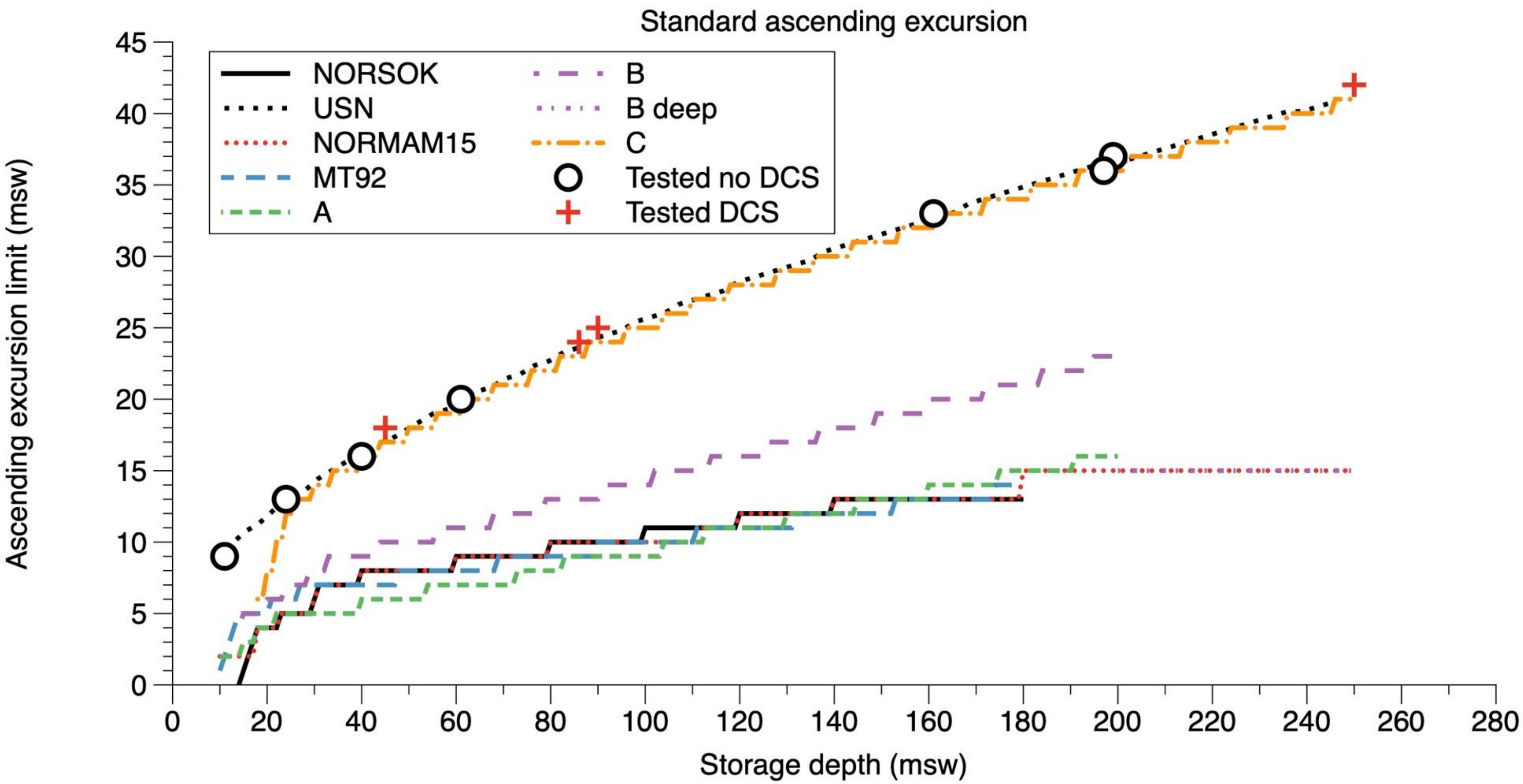

Figure 12 Standard ascending excursion range for storage depth not exceeding 250 msw. Symbolls indicate excursions experimentally tested[1]

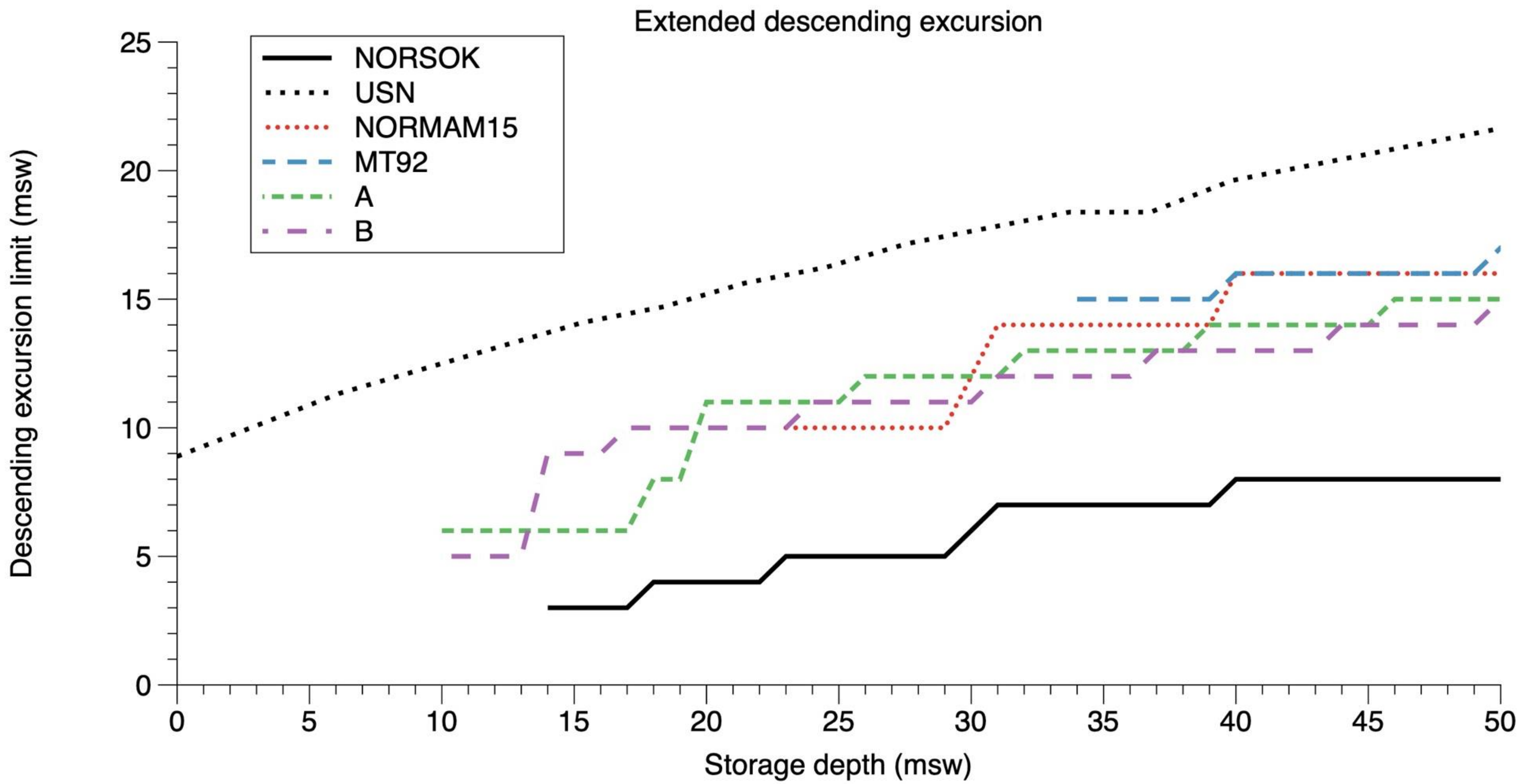

Figure 13 Extended descending excursion range for storage depth not exceeding 50 msw.

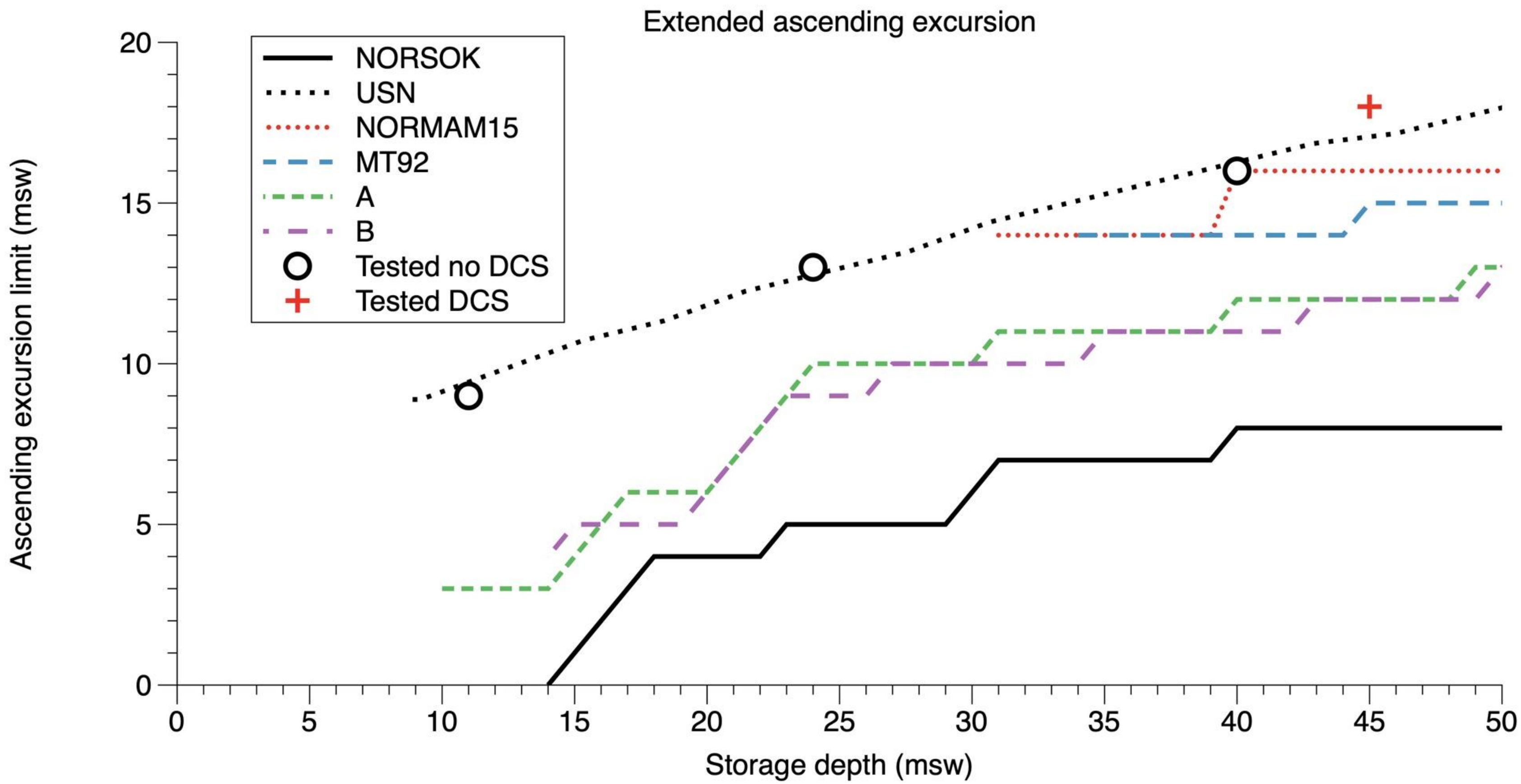

Figure 14 Extended ascending excursion range for storage depth not exceeding 50 msw. Symbols indicate excursion ranges experimentally tested[1].

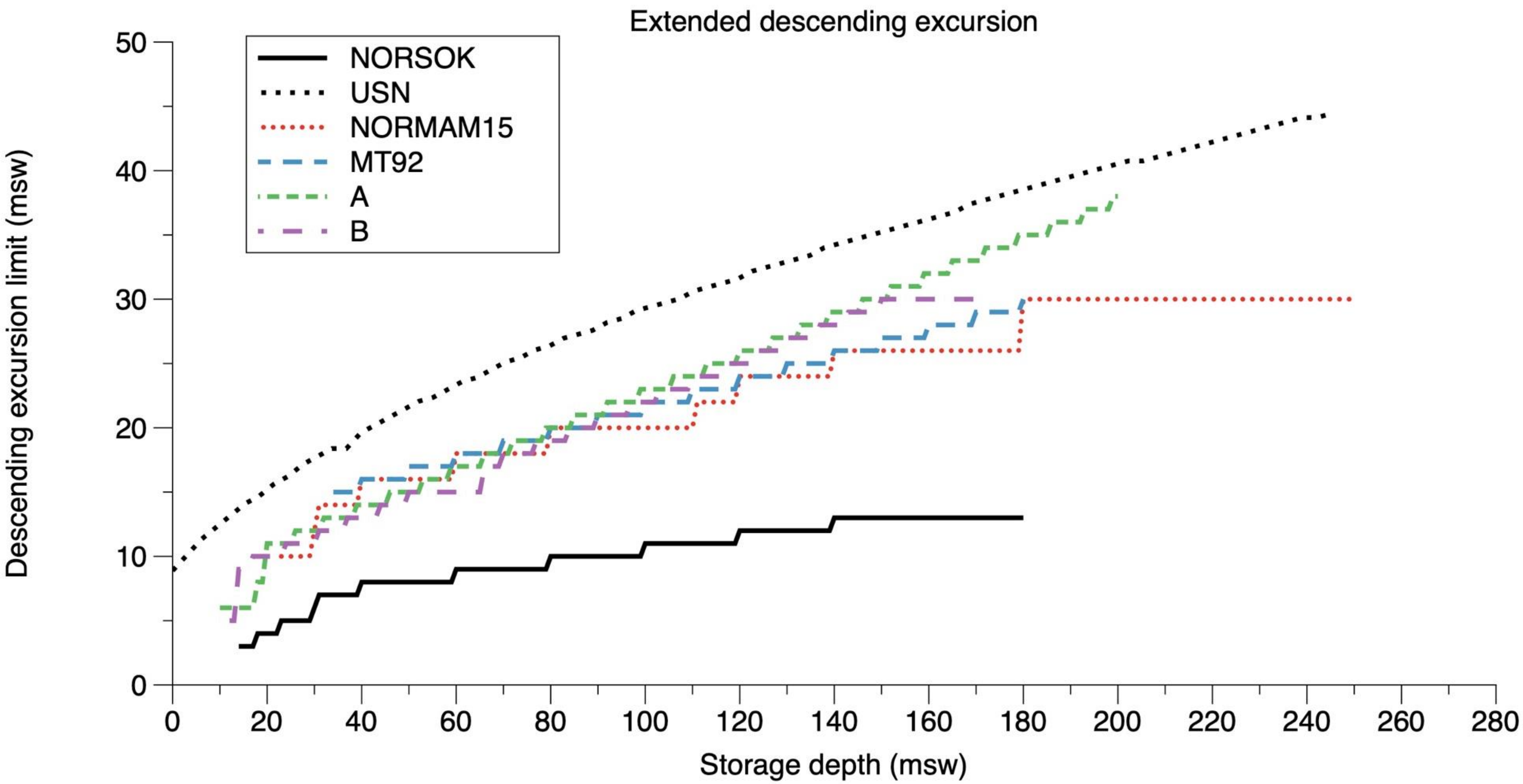

Figure 15 Extended descending excursion range for storage depth not exceeding 250 msw.

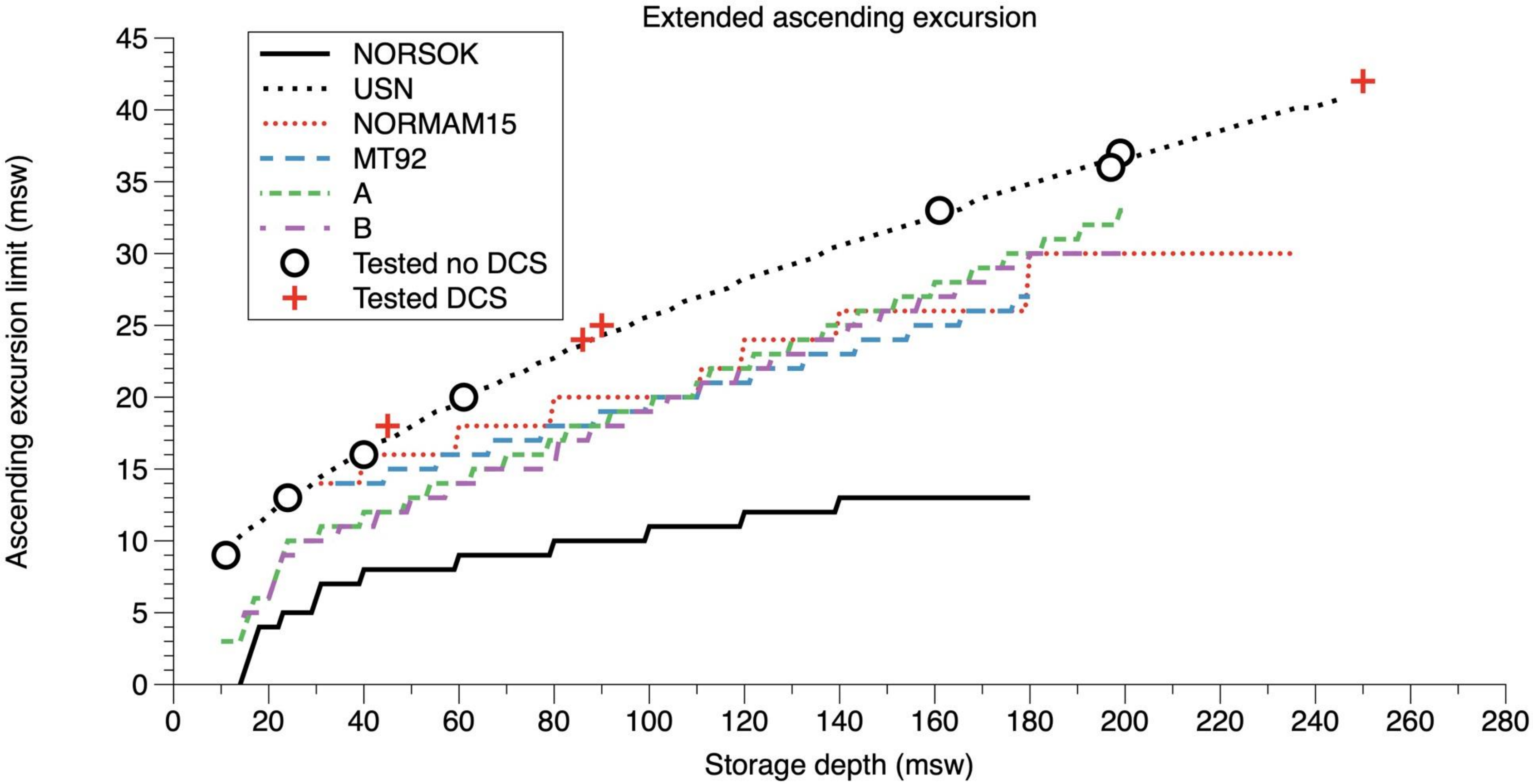

Figure 16 Extended ascending excursion range for storage depth not exceeding 250 msw. Symbols indicate excursion ranges experimentally tested (Thalmann ED, Undersea Biomed Res 1989;16(3): 195-218).