PROBLEMS IN SELECTING A DECOMPRESSION TABLE FOR SATURATION DIVING FOR COMMERCIAL PURPOSES IN POLAND. PART I

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ABSTRACT

The article analyzes the issue of saturation diving needs within the Polish Baltic shelf. The existing and proven saturation diving systems used worldwide are reviewed and compared, and differences, similarities and development trends are identified. The boundary conditions to which all diving technologies must conform are discussed, as well as the directions and trends in development.
A range of possibilities were identified as to which of the technologies used to date are most suited to the conditions in the southern Baltic. Furthermore, it was found that the saturation conditions devised in Poland at the end of the twentieth century, with the participation of one of the co-authors of the article, were in line with the currently considered leading technologies.
Keywords: saturation diving, saturation plateau decompression methods, decompression rates, safe diving zone, partial pressure, breathing mixtures, heliox.

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INTRODUCTION

It has been 30 years since saturation diving was first used in our country on the Polish offshore, even though at that time Poland possessed two research onshore systems and a technology that had been developed, but tested only under the conditions of remote trials in the shipyard. What was lacking to cater for the oil production needs on the Polish shelf was an operational diving system and the relevant national formal documents for conducting saturation dives. Therefore, in the initial period, the Italian company RANA was contracted to secure the Af-2 mobile diving system and a team of Italian divers, completed by a team from the Department of Diving Equipment and Underwater Works Technology at the Polish Naval Academy. The cooperation between the PNV and Rana continued until early 2011. Fluctuations in oil prices and the crash in this market meant that the Af-2 system remained in the country from 1999 as a base for the above Department's research. In the meantime, it has also changed ownership, which since 2004 has been the oil and gas exploration company LOTOS Petrobaltic, and since 2011 underwater works have been based exclusively on the Polish team.

The diving system remains in operation to this day and has been continuously modernised in its more than forty years of use by the team at the Institute of Underwater Works Technology (now the Department of Underwater Works Technology) at the Polish Naval Academy under the supervision of RINA (the Italian classification society) and the Polish Register of Shipping. In addition to the technical and organisational changes, diving technologies were also evolving, particularly decompression procedures as a result of changes associated with various developments, in-house research and trends among the leading countries in the use of this 'high technology' diving.

THE ISSUE OF SELECTING DECOMPRESSION TABLES FOR SATURATION DIVING

When it comes to saturation diving, we are faced with three main decompression issues. These are:

- decompression from the saturation plateau,
- decompression when diving at depths lower or higher than the saturation plateau including the determination of so-called 'no-decompression' times and depths,
- and emergency procedures including accelerated decompression time and evacuation of divers.

They create a system linked to the existing technology and medical base, and define the procedures and technology for diving and underwater operations.

The article focuses on the decompression tables used in the selected countries in connection with the urgent need to choose a new, or improve the current saturation diving technology used in Poland.

The technology currently in use was developed at the Department of Diving Equipment and Underwater Works Technology [1] based on the Polish Navy's existing technical base. The experience of 30 operational years and the saturation dives already routinely carried out in the Naval Academy for training purposes indicate that there is an urgent need for further development of this technology. Our country, despite having official decompression tables for deep-sea diving in the form of a state document [2] does not have official tables for saturation diving. The inclusion of these specific tables in the regulation has become a factor inhibiting the development of commercial diving in Poland, which, however, is a topic for a separate article.

Many diving companies around the world use US Navy saturation procedures. These procedures are constantly being modified to comply with the latest requirements for the prevention of risks from exposure to hyperbaric environments. Owing to problems with research capacity and in particular financial constraints, many companies modify these tables only empirically. As a result, an analysis of the documents on the basis of which these firms conduct saturation diving shows that some of the proposed modifications are technically, legally and, above all, medically unacceptable. Consequently, such manuals may be rejected by strict clients or may expose the companies implementing the procedures described in these documents to consequences should an accident occur. [3] The above shared view of French and British specialists applies mainly to markets where the leading countries in the development of decompression tables for saturation diving compete.

During the saturation dives performed in our country, modified technologies based on US Navy tables were used from the very beginning, even though in 1989 our own tables were developed for domestically made systems. In dives for the Petrobaltic company from 1995 to 2011, tables from the Italian company RANA were used for understandable reasons.

In the case of Polish technology for saturation diving, the latest, up-to-date US Navy tables were also taken into account with decompression modifications; e.g. isobaric decompression was used at the beginning of the decompression. In addition, these adjustments were not limited to the decompression algorithm, but also to the decompression procedures, taking into account the dive technique and safety features. An example of this is the measurement of the partial pressure of oxygen and carbon dioxide with two independent measurement methods. The system for control and maintenance of the chamber's atmospheric composition was based on full digitalisation of measurements and independently conducted analogue measurements. The accuracy of pressure measurements was a class higher than required by regulations and normative documents. This principle of multiple security is still employed by the Department of Underwater Works Technology at the Polish Naval Academy; during training saturation dives, the partial pressures of gases are monitored automatically by 3 independent systems and, as an additional measure, gas samples are analysed in the laboratory during the dive.

Despite the challenging conditions in the Baltic Sea, using the Af-2, the only mobile diving system in Poland, which has been upgraded twice (built back in 1977-1978), no decompression incident was recorded during underwater works until 2023, despite the fact that opinions from some national medical communities [4] suggested the existence of critical supersaturation and the risk of such an incident.

Following the observations of the direction of modifications to the decompression tables for saturation diving employed on offshore in the last thirty years and following the research and new normative documents promoted by international organizations and institutions, we present a brief analysis of the tables used for the 40 - 100 m depth range or the zone of interest in the Polish economic zone in the Baltic Sea.

The selection of official tables for saturation diving in Poland, which will be the basis for further development of tables for underwater service companies, taking into account their technology, medical and technical protection and organisational capabilities, is a pressing need to ensure the future of this strategic type of underwater activity. This problem is equally important for the defence, the widely understood ecology and the energy economy of our country. The knowledge and technology derived from saturation diving is used not only at sea, but e.g. in construction for tunnelling, in mining (retrieving miners from sunken adits) and industry at large, in particular the defence sector.

When implementing new technologies for deep-sea diving, it is important to prevent the mistake that was made when tables for deep-sea diving were introduced by regulation, which did not take into account the diving techniques available in Poland. A misconception had been imposed that the tables could only be introduced by medical specialists, who, as practice shows, base their assessment of the tables on the decompression model used, where there is more mathematics than issues of underwater physiology and, above all, do not take into account the available technique. Imposing solutions instead of developing them among specialists, and in particular ignoring the voice of those who have had the most experience in the field of saturation and deep-sea diving in Poland, has led to the current situation. The sense of urgency in solving the problem stems from the fact that many of the implementers of these dives in our country, whose experience and knowledge was essential, have left for the 'eternal watch' or are sadly preparing to do so. The argument that 'we will bring in or ask specialists in this field from abroad' and that the new national team, if created, will not be burdened with previous practice are absurd, since the most important factor for the implementation of the new tables is the knowledge of Polish conditions, which should be taken into account by Polish specialists.

The intention of this article is to highlight what basic information should be included in the documents of a system of tables for saturation diving necessary for the safe work of diving, medical and engineering personnel to execute and secure dives. In this paper we do not address the problem of tables for air and nitrox saturation dives, as there is no urgent need for their use for commercial purposes in Poland at the present time; in the 20-40 metre depth zone, the underwater work market applies short-term dives. The need for such dives will probably arise when work at intermediate depths is intensified for offshore wind energy, or the construction of tunnels.

We believe that deep-sea diving will not be in demand in the foreseeable future owing to ecological trends, as it is mainly used to secure the extraction of liquid and gaseous minerals and because of the widespread use of diverless technologies. However, in the future, the global economy will need them not only in the areas of subsea mining, but also in subsea construction, defence and environmental protection.

General information on the implementation of decompression in saturation diving

One of the technical and physiological problems of ensuring the quality of the decompression of a saturation dive, i.e. mapping the decompression tables, is the maintenance of the oxygen partial pressure during pressure reduction.

In decompression modelling for saturation dives, two models of tissue saturation of the diver's body are predominant:

- exponential – associated with variable depressurisation gradients increasing with the decrease in absolute pressure. The rates of pressure reduction over time represent an exponential modelling the decreasing basis of the tissue saturation gradient.
- linear – associated with a linear decrease in pressure; two or more gradients of a straight line showing the decrease in pressure underlying the tissue saturation gradient.

If it were not for the restrictions resulting from the possibility of exceeding the safe oxygen content of the chamber (25%), the rate could be constant to the surface and the decompression could be shorter. At the standard oxygen partial pressure used in decompression of 0.4 ata to maintain its value near the surface, the oxygen content would be close to 40%. Uniform rates from the beginning to the end of decompression are not possible due to the above considerations and this applies to all tables used for saturation dives. This is why the tables 'slow down' in the 15 – 0 m depth zone as a result of a decrease in the partial pressure of oxygen, with its content kept constant around 21% according to the changes in pressure inside the chamber.

If the chamber's pO_2 was maintained at 50kPa all the way to the surface, the percentage of oxygen in the chamber would increase to 50 by the time of ascent at a depth close to 0. An oxygen content of a maximum of 23% was assumed from the point of view of fire risk and is maintained from a depth of 15m all the way to the surface. Consequently, the maximum acceptable oxygen percentage is chosen for the final part of the saturation decompression. This value can vary between 20 and 23%. For pO_2 = 50kPa (0.50 ata) 23% is reached at a depth of 11.7m. The decision of the maximum oxygen percentage for the final part of the decompression is based on the fire risk assessment and the technical characteristics of the diving system.

The basis of the decompression model is the so-called 'leading' tissue - 'slow' tissue, which determines the length of decompression. During a short bounce dive, only the so-called 'fast' tissues are fully saturated, with a half saturation time of several minutes or more.

The phenomenon of tissue saturation is assumed to be exponential in time. The half-saturation times of the leading tissue or tissues considered in saturation dives are of the order of several or even several hours (e.g. 240, 360 or more minutes). Naturally, the half-saturation time, determines the full-saturation time of the diver's body. It is taken as 6 half-saturation times of the leading tissue [5,6]. Due to the high cost of testing, the models are only verified for selected saturation plateaux and on a very limited number of experimental divers while the remaining depths are determined by the verified model.

The second important factor in decompression is the oxygen partial pressure used. In very few of the saturation tables currently in use, the oxygen partial pressure is raised to 50kPa (0.5 ba) several hours before the start of decompression and maintained until the oxygen content of the chamber's atmosphere reaches 21-23%. Maintaining a constant value also applies to the partial pressure of carbon dioxide, humidity and temperature in the chamber. When the pressure is lowered, maintaining the permissible pressure of carbon dioxide is achieved by technical means thus increasing the effectiveness of the sorbent. The permissible content of this gas increases with a change in pressure. (e.g. with a permissible pCO_2 = 0.5kPa at a depth of 80m, the permissible carbon dioxide content is 0.056% and at a depth of 20m 0.17%.

Reducing pressure to implement decompression results in a decrease in pO_2. The loss of oxygen caused by the divers' metabolism, which is practically constant throughout the day, plays a part in this reduction. To maintain constant oxygen pressure, oxygen is dosed into the chamber atmosphere. The oxygen dose (during decompression) depends on its rate and varies with decreasing pressure in a function of the natural logarithm. Technical solutions to this problem depend on the method of whether staged or continuous decompression is used and the possibility of homogenising the chamber atmosphere.

In dosing oxygen, it is also necessary to take into account activities that affect the smooth running of the depressurisation. These are maintenance activities such as e.g. the sluicing of meals, materials, changing of linen, hygiene procedures, removal of faecal matter and used bath water, and disinfection of the chamber compartments. These operations must not significantly affect the oxygen content of the chamber atmosphere, hence we compensate for pressure losses with mixtures of similar composition or higher oxygen content compared to the chamber content. The higher the pressure in the chamber, the smaller this impact is, and vice versa. The chamber volume also influences the above-mentioned procedures. These processes are less noticeable when dealing with chambers of larger volumes.

In practice, oxygen supplementation is carried out in two ways: continuous dosing or in portions. During decompression, these are applied as required, taking into account the divers' level of physical effort involved. It is clear that continuous oxygen dosing is preferred during continuous decompression. Achieving homogeneity of the chamber atmosphere is a slow-moving and fluctuating process during depressurisation. The oxygen partial pressure set in the chamber during the entire dive fluctuates within small ranges depending on the accuracy and sensitivity of the measuring instruments, which are also dependent on the conditions in the chamber. Practice requires that life support technicians, in addition to checking the effectiveness of instrument-based oxygen dosing, should check oxygen dosing on the basis of volumes resulting from the loss of oxygen in the tank (e.g. dosing cylinder, etc.). [7]

Each decompression of the divers in a saturation dive, when using heliox mixes on reaching the surface, should be followed by at least 15 minutes in the diving chamber with the hatch open in order to adapt the body to breathing air while exchanging the chamber atmosphere.

Not all tables use stops during decompression.

And the tables where these pauses are used generally do not specify the principle for "managing" the intervals (rest) during decompression. They practically only state the duration of breaks on a 24-hour basis of "up to 8 hours" [7]. Assuming that the current standard is two night breaks of 6 hours and an optional day break of 2 hours, the duration of each full day of decompression will be increased by 6-8 hours. The total decompression time will also depend on when it starts. This is based on whether the last incomplete day of decompression will include a night and or day break. As a general rule, the last decompression interval should end at a minimum depth of 3-4m and, in the case of mobile systems, should take place during the day [1,8,9]. This ensures full control of the process, as at low pressures the operation of the essential equipment must be kept under particular control. In saturation diving systems, many devices work by utilising the pressure difference between the inside of the chamber and the environment e.g. measuring signals, toilet. In practice we encounter decompression procedures using decompression intervals below a depth of 3 m. [9]

The tables currently in use increase the decompression time compared to the tables used in the 1980s and later. The longer the decompression time, the more inefficient it is for the commissioners, but the safer it is for the divers' health and pockets. This is why most companies refine the tables used by introducing decompression breaks, even though they do not appear in the source tables. [3,10].

In the last decade, studies have emerged on the decompression quality of saturation dives from the point of view of the health and wellbeing of the divers, resulting, as in the case of Norway, in changes to the normative standards for these dives [3,7,11,12,13].

The decompression regime for saturation dives is similar in all tables used worldwide. E.g. the maximum time to stay under pressure is 28 days and the minimum interval between two saturations will be the same as the saturation time and cannot be less than 14 days. The maximum time allowed to remain in saturation over a period of 12 consecutive months must not exceed 120 days. The same applies to flight after decompression of saturation dives, a minimum of 24 hours after completion. No document specifies whether the end of decompression also includes the period of time the divers are in the vicinity of the chamber, the so-called "bable time", or whether decompression ends when the divers leave the chamber. Medical indications suggest a longer period between the end of decompression following a saturation dive and a flight: 48 hours, as after treatment of a diving accident.

THE CHOICE OF THE SATURATION PLATEAU

The length of decompression time for a saturation dive is defined by the determination of the plateau depending on the divers working depth. This is also decided by a table of 'excursions' i.e. greater and lesser working depths in relation to the saturation plateau depth. This table gives times and depths relative to the plateau depth. In the case of an excursion 'downward', they provide the limits of time and depths greater than the plateau depth from which no decompression is required to return to the plateau depth. leczeniu wypadku nurkowego.

(Unlimited Duration Downward Excursion Limits). If an upward excursion is used, i.e. a dive to a depth lesser than the saturation plateau (Unlimited Duration Upward Excursion Limits), they specify times and depths for safety reasons, i.e. to protect the diver from a decompression incident.

When exceeding decompression time limits on downward excursions, suitable decompression tables must be applied. The simplest solution is to select tables from a given short dive table system by inserting the saturation plateau pressure in place of atmospheric pressure.

It should be borne in mind that many of the data in decompression tables, particularly in saturation dives, are the results of model calculations, as it is physically and temporally impossible to verify them due not only to the high financial and organisational outlay, but also to the overwhelming influence of bioethics committees effectively limiting the possibility of experiments involving humans. Excursion tables also have a decisive impact on the choice of emergency decompression when it is necessary to shorten the baseline decompression e.g. when divers are evacuated. Research data from the last two decades signal a new approach to the problem of oxygen toxicity, [14] which is also reflected in decompression procedures if we take the US Navy saturation tables as the standard [9].

It is strictly advised in the procedures not to initiate decompression by a so-called 'permissible upward excursion' even with the use of so-called isobaric decompression by increasing the oxygen partial pressure and a defined time of its exposure to the saturation plateau. This entails risks and can only be used under emergency conditions involving the need to shorten decompression.

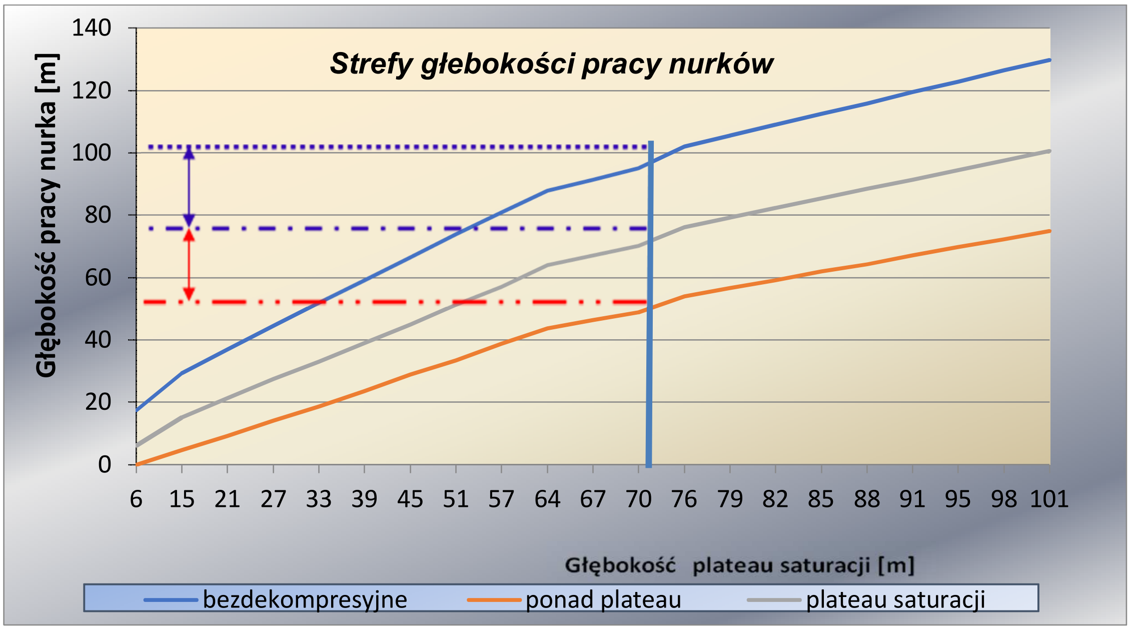

Fig. 1. Overview of diver's depth zones in the water during saturation dives.

Fig. 1 illustrates the selection of the diver's working depth zone. The vertical line cuts off the non-decompression depths from the selected plateau, the intersection with the depth lines delineates the diver's work zones and the limitations of the diver's stay in the water. Planned diver work should take place in the depth zone between the purple and blue lines. The diver's work between the depths delimited by the blue and red lines should be used to a limited extent and most safely avoided.

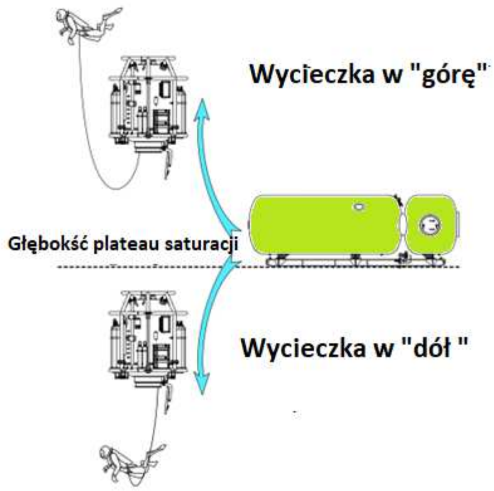

Fig. 2. Diver's working depths in relation to the saturation plateau depth. Options for the position of the diving bell and the position of the diver in the excursion depth zone – [figure from item [3]].

As a general rule, this is a zone restricted by the adopted excursion tables for the return of divers to the bell not requiring decompression.

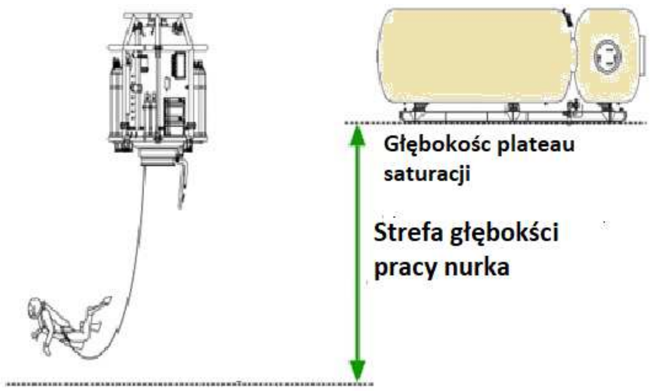

Fig. 3 The most typical position in the works in the Baltic Sea [Position drawing [3]].

Excursions, or diving from a saturation plateau, can be accomplished in three ways. The first is to manoeuvre the bell to a depth close to the working depth, so that the oxygen partial pressure does not exceed the value assumed for the excursion. The second is to position the bell at the saturation plateau depth with the diver diving to the working depth. The third is a combination of the previous methods. The choice depends on two main parameters; the length of the diver's cable/hose harness connected to the bell system (30m recommended) and the distance of the diver's work area.

Based on practice and experience in the Baltic Sea, excursions above the saturation plateau and decompression excursions should generally be avoided [1,8].

Given that underwater works on the Baltic shelf are among the so-called shallow saturation dives (up to 100m), short intervention works are carried out using the "bounce" method, i.e. short duration dives. Working dives are also complementary in terms of some of the breathing mixtures used and can be carried out with emergency mixtures for saturation dives in case of an interruption of decompression or emergency decompression. By contrast, saturation diving is an emergency procedure in the case of "forced extensions" of allowable stay times for deep dive tables.

REVIEW OF SELECTED DECOMPRESSION TABLES FOR SATURATION DIVING

PRINCIPLES ADOPTED IN THE DESIGN OF DECOMPRESSION TABLES FOR SATURATION DIVING

Our country faces the problem as to what criteria to adopt for the selection of decompression tables for saturation diving. Decompression from the point of view of the commissioner and the organiser of underwater work is "not useful"; it reduces the efficiency of the diver's work, even though it is imperative for the safety of the divers. From this point of view, it should be as short as possible. Whereas, from the point of view of the diving team, the opposite is true; it should be as long as possible for reasons of the immediate and far-reaching health consequences of diving. This is also beneficial for financial reasons, as the gratification of saturation divers is high and manifold on the scale of a day's stay under pressure.

Prolonged decompression may carry risks of damage to health resulting from prolonged breathing at elevated oxygen partial pressure, breathing lighter mixtures in the case of helium and heavier mixtures in the case of nitrox, exhaustion and psychological stress, and microbiological hazards resulting from the confined space, maintained thermal comfort, periodically elevated humidity and the specificity of the breathing mixture. The diver's skin is particularly susceptible to infection, as many hours of maceration of the epidermis with seawater while working in the depths causes significant disruption of the skin's protective functions.

It should be noted that when performing decompression for saturation dives, unlike other dives, we can modify the decompression. However, it is only to improve the safety of the divers by slowing down the rate of depressurisation, lengthen the breaks, alter the oxygen partial pressure, and carry out therapeutic recompression during the decompression. Moreover, several saturation plateaus can be used for decompression during the transition from one to the other.

As mentioned earlier, modern tables provide the choice of implementing decompression by continuous method based on linear depressurisation and by staged decompression implemented by 'staged depressurisation'. Both methods are considered equivalent, albeit with their own distinctive characteristics. Staged decompression starts with a greater "jump" in pressure drop when isobaric decompression is used (e.g. 1 or 2 hours prior to depressurisation, oxygen partial pressure increases to 0.6 ata to reach the required oxygen partial pressure after the depressurisation jump [9]).

The use of isobaric decompression in saturation diving was already applied in the Polish tables developed in 1989 [15].

In the modern trends towards shorter decompression of saturation dives and the requirements of underwater physiology, it would be desirable for the rate to be constant all the way to the surface. This change is necessitated by the maintenance of oxygen content in the chamber atmosphere for fire safety, which in turn necessitates an increase in the decompression time. This restriction implies a reduction in the rate of depressurisation. Therefore, decompression from the saturation plateau at the current stage of development and with the current state of knowledge will always be a minimum of two stages; with a decrease in speed at depth zones from 20 - 15m to the surface.

Increasing the pressure reduction rate is only used in decompression acceleration emergency tables and decreasing the rate in therapeutic recompression processes and cases involving incidents of basic decompression.

Decompression tables for saturation dives in US Navy

In many studies on decompression for saturation dives, the US Navy tables are the ones that serve as comparison tables. They form a full system, including emergency tables, discontinuation tables, therapeutic recompression tables as well as giving organisational, technical and medical requirements for their implementation. These tables use heliox throughout the depth range for a saturation plateau from 30m to 488m. It would appear that no accuracy is given in the tables for determining the parameters of atmospheric composition. However, these requirements are in the documents accompanying the US fleet diving regime. Also, in order not to repeat ourselves in describing other tables, we present a broader characterisation of the US Navy tables, as the problems of implementing all the tables are similar or convergent.

Despite the fact that the description of the tables contained in the US Navy Diving Manual clearly cautions against the consequences of their use, many companies adopt or have adopted them to suit their needs. This was also the case of the Italian company RANA, which created its tables based on the US Navy tables, changing atmospheric parameters and excursion tables. Using these tables, the first operational saturation dives were conducted on the Polish shelf.

The control of the bell and chamber atmosphere should meet the requirements of Table 1.

Tab. 1

Oxygen parameters and time limits [acc. to 9[1999].

Diving phase	Oxygen partial pressure	Exposure time
Saturation plateau	0.44-0.48 ata	Unlimited
Excursions	0.40-0.60ata	4 hours (6 hours)***
Wycieczki z dekompresją	0.42-0.48* ata	Unlimited
Emergency decompression	0.60**ata	24 hours

*Notes: * This level may be exceeded in an "upward" excursion for decompression.*
*** If pO_2 pressures exceeds the limit, it is required to switch to emergency mixtures.*
**** Diver's ability to perform decreases exponentially between 4 and 6 hours in the water.*

Specific parameters, in particular of oxygen, are necessary for safe decompression and the use of excursion tables of unlimited duration. Increases in oxygen partial pressure above 0.6 ata for prolonged periods (longer than 24 hours) risk lung damage and should only be used in emergency situations. A pO_2 pressure below 0.42 ata can result in a decompression incident and a pO_2 below 0.16 ata results in hypoxia. When pCO2 pressures reach 0.005 ata; 0.5 per cent surface equivalent (3.8 millimetres of mercury column) for 1 hour, the situation should be counteracted. A level of pCO_2= 0.02 ata (2% surface equivalent SEV; 15.2 millimetres of mercury column) can be tolerated for periods of up to 4 hours at depth for the purpose of decompression. [9; 1999]. Prior to decompression, the atmosphere is required to maintain the assumed parameters, the same applies to the mixture breathed by the diver during the excursion.

According to the US Navy's saturation tables, decompression can be carried out using the staged or continuous method. Alternatively, it is possible to initiate staged decompression and then switch to its continuous variant.

Tab. 2

US Navy saturation dive decompression rate [9].

Depth zone	Pressure reduction rate
1.600 – 200 fwc (488-61m) H_2O	6 feet/hour (1.83m/h)
200 – 100 fwc (61-30.5m) H_2O	5 stóp/h. (1,53m/h)
100 – 50 fwc (30.5-15.25m) H_2O	4 stopy/h. (1,22m/h)
50 – 0 fwc (15.25-0m) H_2O	3 stopy/h. (0,92,3m/h)

Decompression can be started by a minimum of 2 hours after the diver's excursion. Breaks in depressurisation for rest; a total of 8 hours in every 24 hours. The depressurisation lasts for 16 hours in a 24 hour cycle and can be continued while the divers are sleeping.

The 8-hour pause should be divided into a minimum of two rest stops. What times these rest stops take place depends on the daily routine and dive plan.

Staged decompression in saturation is performed at 1 foot increments, not exceeding a rate of 1 fwc/min. For example, taking a rate of 6 feet per hour will decompress the chamber by 1 foot every 10 minutes.

A final decompression stop before ascent may be made at a depth of 4 fwc to ensure that no premature ascent would occur and that gas would flow to the instrumentation monitoring the atmosphere. This last stop would last 80 minutes, followed by a direct ascent to the surface at 1 fwc/min.

Decompression provides for two 'increased depressurisation surges'. The first after the start of decompression and the second at the end before reaching the surface. Approximately 1 hour prior to the start of the surge, the pO_2 in the chamber can be increased to a maximum of 0.6 ata to compensate so that the pO_2 after depressurisation does not exceed 0.48 ata. Reducing the pressure during the first surge from a depth of 200 fwc ($61mH_2O$) or shallower, from a pO_2 valueof 0.6 ata will result in a pressure below 0.44 ata. In such cases, pO_2 should be increased as quickly as possible. As depth decreases, the oxygen content fraction required to maintain a given partial pressure increases. If the pO_2 in the chamber was maintained at 0.44 - 0.48 ata all the way to the surface, the % of oxygen in the chamber would increase to 44 - 48%. Therefore, for the final part of the decompression from 15 m onwards, we maintain a constant acceptable oxygen % of 19 - 23%. The maximum oxygen % for the final part of decompression must not exceed 23, given the risk of fire. If continuous decompression is used, decompression will start with a pO2 setting of 0.48 ata.

Under Polish conditions, continuous decompression was implemented and an isobaric decompression was introduced 4 h before the decompression proper, raising the pO_2 to 0.5 ata.

EMERGENCY DISCONTINUATION OF A SATURATION DIVE

US Navy tables allow for non-adherence to formal saturation dive decompression procedures in extraordinary circumstances. Emergency procedures should only be used in unforeseen situations that require a change or non-adherence to decompression procedures.

These include:

- failure of critical equipment and associated technology that cannot be rectified and compensated for within the functional and structural redundancy structure of the diving system,
- failure and breakdown of safety technology or diving support equipment,
- a life or health-threatening medical emergency in which the risk of not transferring the patient to a more specialised medical facility outweighs the increased risk of pulmonary oxygen toxicity and increased risk of decompression sickness associated with failure to comply with standard decompression saturation procedures [9].

A procedure for aborting a dive in an emergency that has been tested to a limited extent. It allows divers to ascend earlier than would normally be allowed. Naturally, the execution of the emergency aborted dive procedure significantly increases the risk of decompression sickness and oxygen toxicity related complications. The underlying reason for aborting a dive and applying emergency decompression is to determine whether the time saved will have a beneficial effect on the diver's life despite the increased risk, and whether the emergency abort procedure has the logistical support.

The saturation diving system has all the technical and organisational multiple redundancies for high safety to protect the diver's life. Still, there may be emergencies whose nature or reduced time sensitivity will not allow deviation from standard decompression procedures.

Tab. 3.

Emergency decompression interruption times and oxygen partial pressures. [9].

Depth	pO2 (ata)	Retention time per one foot (min)	
		1000–200 fwc	200–0 fsw
0–203	0.8	11	0–203
204–272	0.7	11	204–272
273–1000	0.6	12	273–1000

Emergency decompression is commenced by performing the maximum upward surge allowed in the excursion table. The rate of depressurisation should not exceed 2 fwc/min. The depressurisation should be followed by a 2-hour stop at the limit of the upward gradient. The time to reach this depth is included in the 2-hour stop. After the upward excursion, the partial oxygen pressure in the chamber rises to the value shown in Table 3, depending on the depth.

Decompression should be continued at 1 foot intervals according to the times indicated in the table. The rate of pressure change between stops must not exceed 1 fwc/min. This time is included in the time of the next stop.

The oxygen partial pressure is controlled to the indicated value until it reaches 23%. Then between 19 and 23% for the remainder of the decompression. As in staged decompression at a depth of 4 fwc we stop until the total decompression time is reached and then to the surface at a rate of 1 fwc/min.

Divers should be closely monitored during and after the dive for signs of decompression sickness and symptoms of pulmonary oxygen toxicity. Divers should be under close observation for at least 24 hours following the dive. If an emergency situation no longer exists during decompression, decompression should be halted for at least 2 hours and then the decompression should be returned to standard decompression rates and the oxygen partial pressure should be allowed to fall to normal control values, by way of the divers' oxygen consumption.

Conclusions from the US Navy diving system for our country

As can be seen from the foregoing, the provision or adoption of 'dry' dive tables especially for saturation diving is a great oversight or rather a failure to recognise the problem. Tables must be provided in a whole system comprising working tables, emergency tables (compression interruption, plateau stay - emergency decompression), working excursion tables, and a system of therapeutic recompression tables. The tables must not be separated from the technical and logistical support techniques in place and the organisation of the diving system and the organisation of the diver's evacuation in a given country.

In Poland, the role of securing full-scale saturation diving was in the first period performed by the Navy, and in the first twenty years of the 21st century by the Naval Academy; the only company with the technology to perform saturation diving is LOTOS Petrobaltic. Whereas the resources in the field of medical security were available from the Military Medical Academy, the Department of Maritime and Tropical Medicine.

The Navy, the companies exploiting underwater deposits, the power industry and possibly also ecology-related underwater research should jointly participate in maintaining our country's saturation diving potential. This will allow to sustain the potential for saturation diving in adequate readiness for the needs of Poland's economic and defence policy and reduce the costs of upkeep of this branch of underwater activity, which, it should be emphasised, is the only one in the Baltic region.

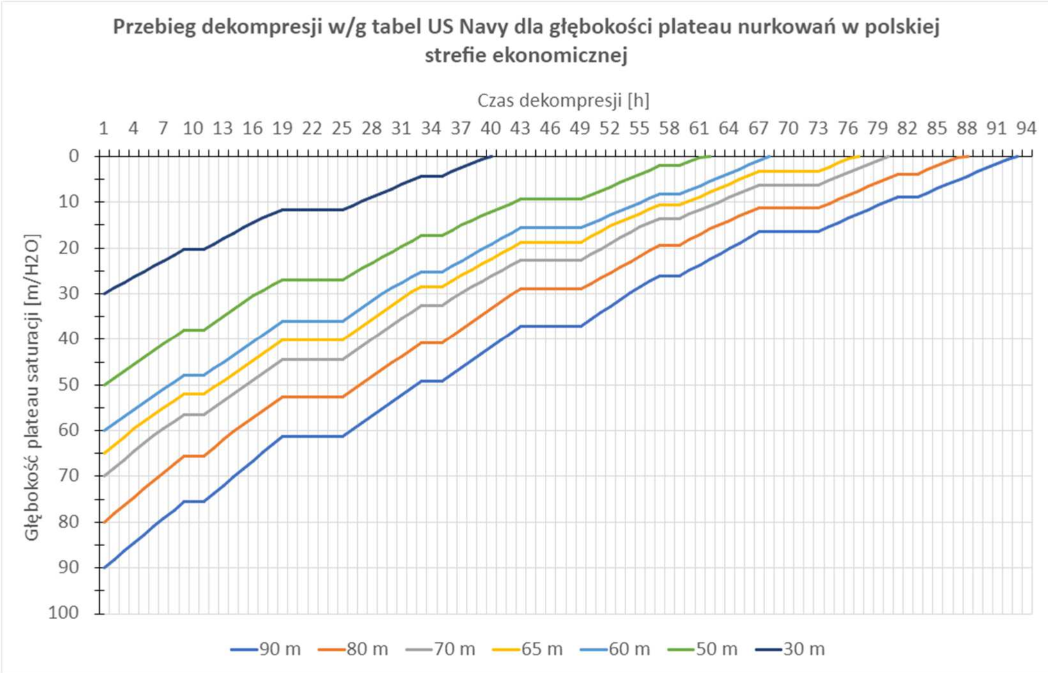

Fig. 4. Decompression schedules according to US Navy tables for selected saturation plateaus for underwater works recommended for use in the Polish Economic Zone in the Baltic Sea.

By only assuming the use of downward excursions, we have the possibility to "manoeuvre" the saturation plateau adjustment in the dive so as to apply a decompression-free return of the divers to the plateau.

TABLES OF THE ITALIAN COMPANY RANA USED DURING SATURATION DIVES IN OUR COUNTRY

TABLES DATA USED IN THE 1990S

The RANA company used the decompression table system based on the 1980 US Navy tables in which air or a heliox mixture with 20% oxygen could be used during compression and decompression in the 0 - 6m depth zone. They used air from 6.5m and vice versa, which at that depth had an assumed oxygen partial pressure pO_2=0.34 ata.

The chamber's atmosphere was obtained by air compression to a depth of 6.5 metres followed by pressurisation with pure helium to the assumed depth. Homogeneity of the mixture was achieved by intensive ventilation with life support system blowers and internal carbon dioxide canisters. The operation of both the internal ventilators and the external life support circuit ensured that divers only breathed from inhalers during the initial compression phase. Regardless of whether it was a saturation or decompression period, the atmosphere in the chamber was maintained within the following limits (an original procedure record):

Nitrogen – pN_2 =1330 mbar. (corresponding to the dept for air of 6.5 H_2O).

Oxygen - pO_2= 332 mean value (range from 265 to 465 mbar)

Carbon dioxide - pCO_2 not higher than 2,6 mbar equivalent to 0,25% (at the sea level).

Hel - pHe: pressure balancing saturation plateau pressure

Bell atmosphere (an original procedure record):

Nitrogen – pN_2 not higher than 1330 mbar

Oxygen - pO_2.within limits between 400 and 600 mbar.

Carbon dioxide pCO_2: not higher than 5,2 mbar (0.5% of the equivalent pressure)

Hel - pHe: partial pressure balancing the immersion pressure.

Decompression

The RANA excursion application did not use the US Navy's system, but its own, based on four depth ranges increasing by 7.5m to a saturation plateau between 45 and 90m with time given for the diver to complete the dive without decompression, only the return at a specified ascent rate of 10m/min to the plateau was specified. When these times were exceeded, a system of decompression tables was developed for the diver returning to the bell.

The excursion table was developed with the following requirements: the bell was always submerged to the saturation depth, which differed from the US Navy system, and no upward excursions were envisaged; these were treated as short exceptions of staying within 7.5m above the saturation plateau. *(The Italian managers felt that it was necessary to plan the saturation plateau so that tasks above the plateau were avoided. In collaboration with the Italian team, there were two occasions when the divers performed short, unplanned tasks above the plateau lasting* *a very short time, up to 2 minutes only).*

DECOMPRESSION FROM SATURATION PLATEAU

The decompression employed the requirements of the US Navy system with one night break of 6 hours and depressurisation rates as in Table 2.

As emergency decompression, RANA cited the official national document: Annex 6. Extract from Italian Regulation UNI 11366 "Safety and Health in Hyperbaric and Commercial Diving Activities" "7.3.12 Decompressione di emergenza" and unofficial translation "Emergency decompression", [8] according to Italian specialists based on the US Navy system.

The system of tables used in the 7 saturation dives for commercial purposes in our country differed "7.3.12 Decompressione di emergenza" and unofficial translation "Emergency decompression" [8] oparty wg specjalistów włoskich o system amerykański US Navy.from the original US Navy tables in the conditions during decompression for (pO_2 = 0.33 ata, pN_2 1.32 ata) and the non-use of 2-hour breaks in each 24-hour decompression period. These three deviations significantly increased the exposure of decompressors in the 'RANA' system compared to the US Navy 1973 system, in which the percentage of pressure sickness cases amounted to 11 [4]. This opinion of national underwater medical specialists raised doubts about the collaboration with RANA. They were clarified by Italian specialists claiming that in the shallow saturation range the problem is practically non-existent. Decompression incidents were fortunately not observed, either in Italian or Polish divers.

DECOMPRESSION TABLES USED BY RANA IN THE 21ST CENTURY

The Italians, working in Poland between 2001 and 2011, modified the decompression system based on the US Navy 1991 system. Whether the high risk of performing decompression in the US Navy 1973 system or the assessment of the NEDU (Navy Experimental Diving Unit), which improved the decompression process [4], constituted the basis for this change is unknown. Consideration must also be given to advances in the technical equipment of diving systems in which helium recovery systems were introduced and a closed circuit in the breathing equipment which required a pure two component mixture when recovering helium mixtures.

The US Navy 1991 system of decompressing divers with heliox, as opposed to the 'Rana' system, is safe, however, it is characterised by very long decompression times.

It is worth noting that the discussed US Navy 1991 saturation decompression system (after limiting the decompression rate in the zone to 60 metres and eliminating the 6- and 2-hour stations provided for divers' sleep) was surprisingly similar in parameters to the national saturation decompression system verified back in 1982 - 1989 in the habitat of the Polish Naval Academy's ZSNiTPP [4,10,16]

Using the US Navy 1991 decompression system, the Italian system did not include an 8-hour break, but left a 6-hour break as before during the 24-hour decompression execution period. Before starting decompression, the oxygen partial pressure in the chamber was raised to 0.48 bar. This value must be maintained at 50 fwc. From 50 fwc to the surface oxygen content must be maintained at 21%. Heliox mixtures are used throughout the decompression. During decompression no air may be used for any purpose.

In the event of an emergency, the main principles of the US Navy have been adopted. In the event of an extreme emergency, the life support supervisor must implement the following steps: [17].

- if the emergency involves only part of the team in a state of saturation and the system consists of at least 2 independent hyperbaric chambers, only the diver concerned should perform the accelerated decompression;
- if a single diver is involved in an emergency situation, the external operator should be redeployed to the chamber that will be used for the accelerated decompression so as never to have one diver in the chamber;
- depressurise the chamber at a rate of 0.75 m/min;
- increase and maintain up to 18 m the partial
- pressure of oxygen in the chamber to 650 mbar; (0.85 ata];
- start decompression at the following rates depending on the depth at which decompression is initiated:
- ✓ from 180 to 90 m at 3 m/h,
- ✓ from 90 to 30 m at 2.4 m/h,
- ✓ from 30 to 18 m at 1.2 m/h,
- ✓ from 18 to 0 m at 0.6 m/h,
- ✓ from 18 m chamber ventilation with air;
- never exceed oxygen content in the chamber above 23.5%.

A very important consideration in the accelerated decompression procedure is to assess the real benefit of accelerated decompression time compared to normal prior to the procedure initiation.

SATURATION DIVING DECOMPRESSION TABLES OF USED BY A FRENCH COMPANY COMEX

The COMEX saturation diving tables contain many recommendations not found in other tables, which should be taken into account in the case of selecting these tables. They are a natural development of the heliox tables for deep-sea, short-duration diving, which, unfortunately, are now the "official state tables" contained in the Regulation of the Minister of Health of 17 September 2007 on health conditions for underwater works. [2]

These are tables applying heliox in the zone of applied saturation plateau depths from 10 to 180 m which allows to secure the underwater work of divers in the zone between 10 and 195 m with standard excursions and from 10 to 210 m with exceptional excursions.

Formal French documents (Article 6 of the decree of 28 March 1990) - impose standards for the heliox mixtures that should be used: e.g. for compression they recommend a mixture with 2% oxygen (recommended in DMAC recommendations). They specify the rate of compression; 3 m/min to a saturation plateau depth of 100 metres, they specify the accuracy of depth determination - +/- 0.5 metres. They allow the diver to start diving immediately on reaching the saturation plateau.

Decompression procedures

Downward excursion tables are limited to a depth of 30 metres below the saturation plateau. The immersion time for a working depth "excursion" is limited to a maximum of 2, 4, 6 and 8 hours, depending on the depth of said excursion and is strictly defined in additional tables. Furthermore, working mixtures should be prepared for excursions, as in Polish technology. The tables give the minimum and maximum permissible percentage of oxygen for the excursion "downwards". The composition of the mixture should ensure pO_2 = 500 to 800 millibars.(0.5 to 0.8 ata).

The rate of decompression of the bell from working depth to storage depth is carried out at a rate of 5 metres per minute. The diver's submersion from working depth to the bell should be reduced to a minimum (one or two submersions maximum) and performed at a rate of 5 metres per minute. For instance, from a saturation plateau of 70m the depth for a two hour stay is: 100m - 4 hours, 90m - 6 hours, 85m - 8 hours. For the saturation plateau, each depth is assigned a working heliox mix. For 70m for 2 hours a heliox of 8-12% oxygen and for 8 hours a maximum of 11%. The tables do not provide for upward excursions, which, with such a wide depth zone downwards, allows the selection of an appropriate carbonation plateau.

The mixture setting is only done on an ongoing basis when using closed-loop equipment in a helium recovery system loop. In the current Polish conditions this is not possible with open circuit diving equipment. In this case, the working mixture is prepared for the diver's maximum working depth.

On return from excursions, a 12-hour break is required to start decompression from the saturation plateau. It begins with an ascent of one metre in 10 minutes. This is followed by continuous decompression. The principle applies: 'if decompression is delayed, it should never be accelerated to make up for lost time'.

COMEX decompression tables use two types of decompression for different oxygen partial pressures:

- pO_2 = 600 hPa (not found in other tables) for decompressions from saturation plateaus not exceeding 155 m depth. Only applicable if decompression time is less than 5 days,
- pO_2 = 500 hPa for decompression from a saturation plateau depth of more than 155 m. Only applicable if decompression time is longer than 5 days.

Tab. 4

COMEX decompression data.

No.	Parameter	Saturation plateau from 10 to 155m	Saturation plateau above 155m
1	Oxygen partial pressure	pO_2 = 600 hPa	pO_2 = 500 hPa
2	Oxygen partial pressure holding range	pO_2 = 600 hPa -25 hPa).	pO_2 = 500 hPa to 525 hPa
3	Depressurisation rates from saturation plateau to 15m	45 min/m (1.33m/h)	45 min/m (1.33m/h)
4	Depressurisation rates from 15m to 0 m	60 min/m. (1.00m/h)	60 min/m. (1.00m/h)
5	Oxygen content in the depth zone 15 - 0m	21-24%	21-24%
6	Decompression time	less than 5 days	more than 5 days

The tables also prohibit divers from flying aircraft after decompression for a minimum of 24 hours. The recommended tables for therapeutic recompression in saturation are of two types; heliox and air the same as for short duration air and heliox dives.

The composition of the mixtures used differs from the approach of the US Navy system. At depths greater than 18 metres, oxygen cannot be used due to its toxicity. At deeper depths, mixtures are used, with the series starting at 50/50% oxygen/helium, followed by 35/65% oxygen/helium. There are also heliox mixtures used in operational applications, e.g. those used for deep-sea diving in the Polish shelf area, i.e. 20/80% oxygen/helium and 15/85% oxygen/helium. This is a series of gases that secure an oxygen partial pressure of 0.5 to 2.5 bar at assumed depths. It is recommended that therapeutic heliox is administered in cycles of 20 to 30 minutes. Once full relief has been achieved, treatment can be continued for 1 to 3 cycles. Afterwards, breaks are often taken before decompression is restarted.

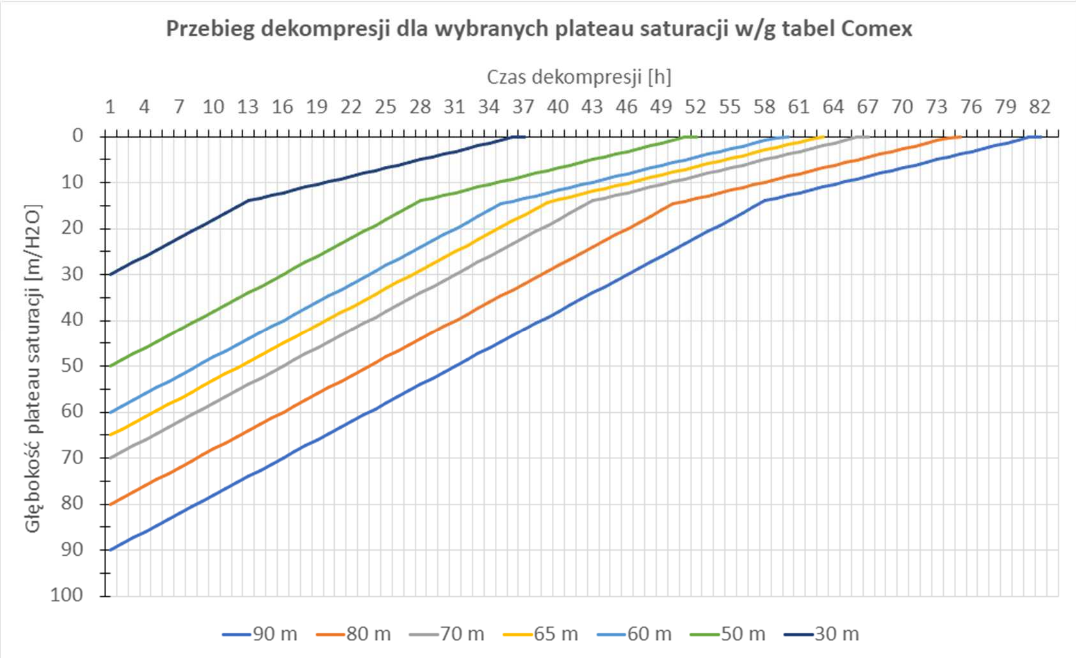

Fig. 5. Decompression schedules for selected saturation plateaus according to COMEX tables for underwater work proposed for use in the Polish Economic Zone in the Baltic Sea.

Saturation diving tables in Great Britain

The RN table (graduated pressure reduction tables (CIRIA System – 1978). Construction Industry Research and Information Association

We describe these tables for historical reasons, as one of the solutions for saturated decompression tables. In this system, a heliox mixture with trace nitrogen content at a level of quantifiability below the partial pressure in air at sea level is used during the plateau and during decompression). For these reasons, the CIRIA system, as uneconomical and with physiologically unjustifiable exposure decompression (stations every 5 metres), remains of no interest for the purpose under consideration. [4]

The table provides for gradual depressurisation in steps of 5 metres or 3 metres, and the maintenance of pO_2 between 0.49 and 0.51 throughout the decompression.

Tab. 5

Table of staged pressure variations during decompression of the CIRIA system.

Plateau depths range	Staged depressurisation	Stop time for a given pressure surge
305 - 180 mwc	every 5 mwc	3 hours
180 - 33 mwc	every 3 mwc	3 hours
30 - 18 mwc	every 3 mwc	4 hours
15 - 3 mwc	every 3 mwc	5 hours

Saturation diving table used by UK company providing services in the North Sea [11,18]

In the UK, the procedures of the companies using the lowest acceptable oxygen levels at the saturation plateau depth and during decompression were selected for the HSE study. The differences between the procedures used by the different companies are negligible in terms of the risk of a decompression incident. The combination of fastest decompression and lowest oxygen levels meant that the worst case was simulated. The depressurisation data are shown in Table 6.

This system uses a continuous decompression profile based, as the French one is, on two rates, 1.5m/h and then 0.6m/h with a 4-hour break in every 24 hours. At the plateau, a pO_2 of 0.35 ata is maintained and during decompression 0.5 ata is maintained with a corresponding adjustment in the 15 - 0 m zone for an oxygen content in the range of 21- 23%.

Tab. 6

Decompression table of the company's saturation dive in the North Sea.

Range of depth zones of change during decompression	Pressure changes rate
350 to 20 m	1.5 m/ h
20 m to 0 m	0.5 m / 50 min (0.6m/h)

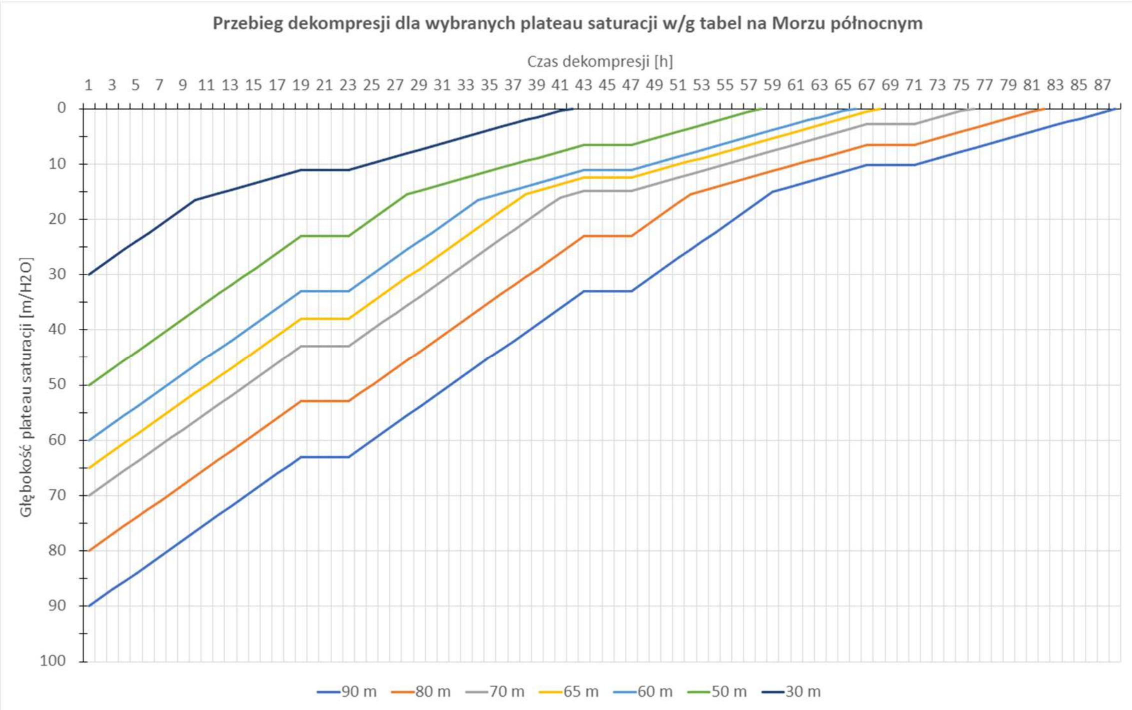

Fig. 6 Decompression schedules for selected saturation plateaus according to North Sea tables for underwater works, proposed for use in the Polish Economic Zone in the Baltic Sea.

SATURATION DIVING DECOMPRESSION ACC. TO US NAVY STANDARD

Decompression can be applied as continuous decompression or staged decompression. The decompression start may be initiated with an upward excursion if permitted by the regulations. Notwithstanding the above, it is generally considered good practice to allow a 4-hour hold period after the completion of the last bell immersion and before the start of the final decompression. Decompressions are carried out without interruption, 24 hours a day, with no restrictions on the diver's sleep or activity. These tables allow decompressions to be performed from a saturation plateau in a continuous linear or staged manner with increments of 1.2m/hr, 0.76m/hr and 0.60m/hr. [19]

Tab. 7

Table of depressurisation during decompression for a saturation dive in the North Sea (with three depressurisation rates).

Range of change depth zones during decompression	Rate of pressure change
1000 - 200 fwc (305 - 61m)	4 fwc/h (1,2m/h.)
200 - 50 fwc (61 - 15,25)	2.5 fwc/h (0,76m/h)
50 fwc – 0 (15,25 - 0)	2 fwc/h.(0,61m/h)

The tables did not provide for breaks (rest for divers), but for several decades the majority of companies have been executing breaks between midnight 00.00 and 06.00 and 14.00 and 16.00, i.e. 8 hours in a day of decompression.

At the saturation plateau, pO_2 is maintained at 0.48 bar - 0.49 bar, and once 23% is reached, the chamber atmosphere is stabilised with no further increase in pO_2 to the surface. If required, decompression can be performed at a lower rate of 1 fwc/h (0.61m/hr). This necessity was defined; we presume it was for emergency decompression during a decompression incident. It is interesting to note that an oxygen content of 30% was allowed. 30% is considered the maximum from a fire protection point of view. Accordingly, for the final part of the saturation decompression, the maximum permissible oxygen percentage was opted for. This maximum percentage was reduced to between 19% and 23%.

Elements such as excursions, aborted decompression and emergency tables are based on 1992 US Navy tables [9].

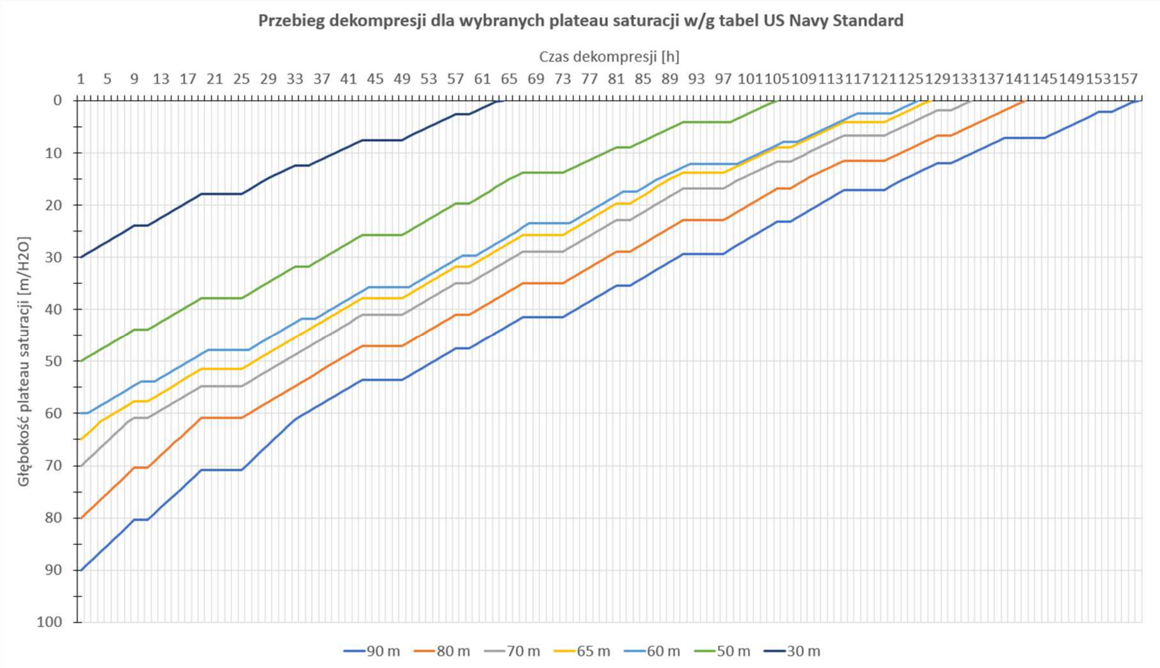

Fig. 7. Decompression schedules for selected saturation plateaus according to US Navy Standard tables for underwater works proposed for use in the Polish Economic Zone in the Baltic Sea.

The Norwegian table - NORSOK STANDARD U-100

The implementation of decompression here has four rates of depressurisation. During decompression from the saturation plateau, pO_2 is maintained in the range of 40 - 50 kPa (400 - 500 mbar). During decompression, a six-hour break is taken every 24 hours. In the final phase of decompression this stop should be between 24:00 and 06:00 and the last stop should end at a depth of more than 3m. [7]

The minimum saturation plateau depth is 14 mwc. The technology does not indicate whether this is with air or nitrox. Heliox is generally used from a depth of 30m.

Tab. 8

Saturation decompression acc. to NORSAOK 101 [7].

Depth mwc	Minut/mwc	mwc/h	mwc/day
180 - 60	40	1.5	27
60 - 30	50	1.2	21.6
30 - 15	60	1	18
15 - 0	80	0.75	13.5

The revolution in these tables compared to others is the excursion table, which itself has been strictly limited, and the description of the tables does not indicate that decompression excursions can be used. If they are longer, special procedures for a longer stay at plateau depth prior to the start of the actual decompression are envisaged. Decompression can be started after a minimum of 8 hours of stay on the plateau after the excursion.

Tab. 9

Table of zero decompression excursions (non-decompression excursions) [7].

Saturation plateau depth [mwc]	Excursion [m]	
	upward	downward
14	0	3
15	1	3
16	2	3
17	3	3
18 do 22	4	4
od 23 do 29	5	5
30	6	6
31 do 39	7	7
40 do 59	8	8
60 do 79	9	9
80 do 99	10	10
100 do 119	11	11
120 do 139	12	12
140 do 180	13	13

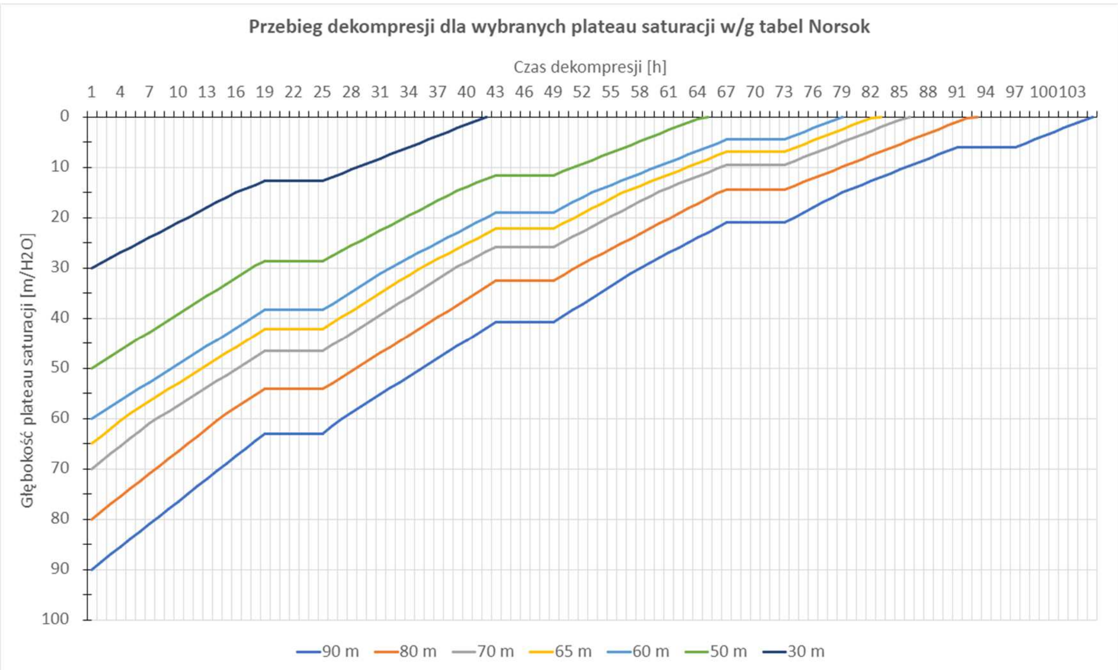

Fig. 8 Decompression schedules for selected saturation plateaus according to NORSOK tables for underwater works, proposed for use in the Polish Economic Zone in the Baltic Sea.

NORMAM-15/DPC DECOMPRESSION TABLES FOR SATURATION DIVES

The NORMAM-15/DPC saturation diving system is the result of research and experience by COMEX specialists. The system and procedures were developed for the Brazilian offshore industry and can be regarded as an improvement on the Comex MT 92 tables, which are still promoted by the French Ministry of Labour, and those used at the beginning of the century by Stolt Offshore. The NORMAM-15/DPC procedures allow safe hyperbaric exposures up to 350m and have been adopted by the Directorate of Ports and Coasts of the Brazilian Navy. They were issued as the official document '*Standards for Underwater Activities*' in 2011. The author of this study and the former Comex specialists working with him believe that saturation dives successfully performed in Brazil and other countries using these procedures are much safer than US Navy procedures [3,12].

The oxygen partial pressure at the saturation plateau of the above-mentioned saturation dive is maintained between 0.38 - 0.45 bar (380 - 450 mb). The remaining atmospheric composition parameters are the same as in other saturation diving systems.

It is assumed that the final pO_2 may exceed 0.450 bar and reach up to 0.570 at the end of the initial pressurisation. No corrective action is required as the excess oxygen in the chamber will be exhausted physiologically by the diver.

The system has two tables of upward and downward excursions: standard and exceptional. Immersion and ascent speeds during excursions should not exceed 10 m/min. It should be mentioned that other diving systems use the same or similar rates. (French decree of 15 May 1992). Exceptional excursions allow greater depths of operation for the diver than standard excursions and are limited by the length of stay. They should only be used in situations of exceptional necessity or emergency.

In saturation diving the 'good diving rules' for excursions also apply as highlighted in the studies [1,3,12]:

- Plan trips downwards rather than upwards. It is recommended that the diving bell is at saturation plateau level, above the working diver.
- Plan diving trips from standard tables rather than exceptional ones.
- Planning of the work should be done to avoid multiple ascents and 'yoyo' dives, i.e. limit the amplitude of the diver's depth changes during the work, especially down and up dives exceeding saturation plateau depths.
- Plan for the saturation plateau to be as close as possible to the working depth.
- Operate the depth of the bell, if necessary, within the limits of standard excursions.

Tab. 10

Depths of standard and exceptional excursions: NORMAM-15/DPC [12].

Saturation plateau	Standard downward excursion	Standard upward excursion	Exception downward excursion	Exceptional upward excursion
[m]	[m]	[m]	[m]	[m]
Up to 10	Not applied	Not applied	Not applied	Not applied
10 to 17	3	2	Not applied	Not applied
18 to 22	4	4	Not applied	Not applied
23 to 29	5	5	10	Not applied
30	6	6	12	Not applied
31 to 39	7	7	14	14
40 to 59	8	8	16	16
60 to 79	9	9	18	18
80 to 99	10	10	20	20
100 to 119	11	11	22	22
120 to 139	12	12	24	24
140 to 179	13	13	26	26
180 to 270	15	15	30	30
270 to 285	15	15	30*	30*
From 270 m, the depth of excursions should be reduced so as not to exceed a depth of 300 m				

The depressurisation rates are given in Table 11.

The decompression procedure from the saturation plateau is the same after standard and exceptional excursions, starting 12 hours after the end of the excursion. From the start of decompression to a depth where the percentage of oxygen in the chamber reaches 25%, an oxygen partial pressure of 0.48 - 0.5 bar should be maintained. From this depth, the percentage of oxygen in the chamber atmosphere is maintained between 21 and 25% due to the risk of fire.

Start of decompression from the staged saturation plateau is carried out respecting the stabilisation periods of the set atmospheric composition, while continuous decompression is started in a smooth manner at the rates given in the table.

Tab. 11

Pressure change parameters during decompression set out in NORMAM-15/DPC.

Depth range	Continuous decompression	Staged decompression
350 to 20 m	50 minut/ 1m (1,2 mwc/h)	Pressure reduction by 1 m every 50 minutes
20 m to the surface	90 minut/1m (0,67 mwc/h)	Pressure reduction by 1 m every 90 minutes

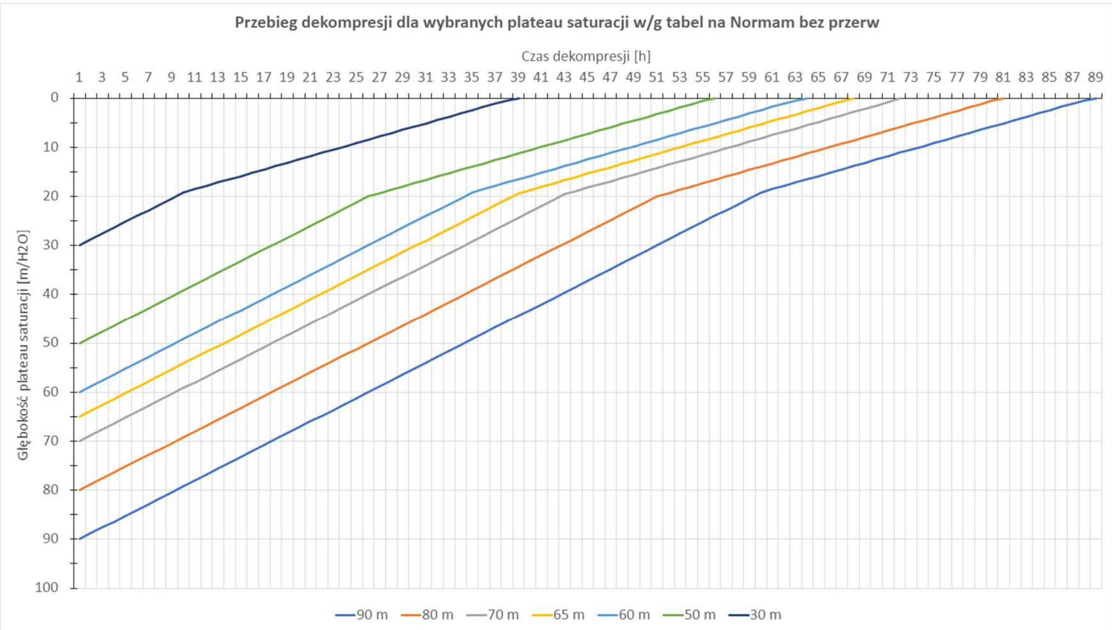

Fig. 9. Decompression schedule for selected saturation plateaus according to NORMAM 15/DPC tables , proposed for use in the Polish Economic Zone in the Baltic Sea.

Decompression courses were modified by introducing 8-hour breaks in the 24-hour interval of the NORMAM tables, which originally do not apply breaks in decompression. Comparing the decompression time using the NORMAM tables for decompression with and without breaks, we see that the decompression time increases by practically 24 hours for every 20 m increase in the saturation plateau depth.

Russian Navy tables of the Russian Navy (or in fact the Soviet Union)

As a historical duty, we give a brief description of these tables, particularly as they were taken into account in planning the implementation of saturation diving also in Poland during the last 50 years. These tables are original due to the use of a trimix mix with step decompression with a constant 2m depressurisation gradient from the saturation plateau to the surface and with increasing holding time at depth as shown in Figure 10. According to an assessment by underwater medical specialists, this method of decompression is also safer than the 'Rana' system, although the high initial decompression rate and the use of graduated depressurisation (stations) raise reasonable doubts [4]. These rapid jumps only occur at greater depths for plateaus in the 150 - 300m range. The depressurisation rates decrease with depth and are lower than the rates for the emergency tables for heliox mixtures. This results in prolonged decompression, even though it does not provide for breaks. However, stopping times of 60 to 320 minutes can be treated as a sequence of breaks with 2m jumps.

The procedures take into account the saturation plateau from depths of 10 - 300 m in offshore conditions for trimix mixtures and 6 - 40 m for nitrox mixtures. During the plateau and decompression, the oxygen partial

Procedury uwzględniają plateau saturacji od głębokości 10 - 300 m w warunkach morskich dla mieszanin trimiksowych i 6 – 40 m dla mieszanin nitroksowych. Podczas pobytu na plateau i dekompresji ciśnienie parcjalne tlenu dla stosownych przedziałów głębokości to 0,35, 0,40 i 0,50 ata.

pressures for the respective depth ranges are 0.35, 0.40 and 0.50 ata.

The time needed to transfer from one stop to another is at least 20 minutes and is included as time spent at the next stop. The tables do not contain a schedule of excursions.

Trimix mixes are used which are based on mixing 1 volume of air and one volume of helium for dives between 40 - 100 m, one volume of air and two volumes of helium for depths between 100 - 160m and 1 volume of air and 3 volumes of helium, resulting in trimixes of 10%O_2, 40%$N_2$50%He , 7%O_2, 26%$N_2$67%He , and 5%O_2, 20%$N_2$75%He.

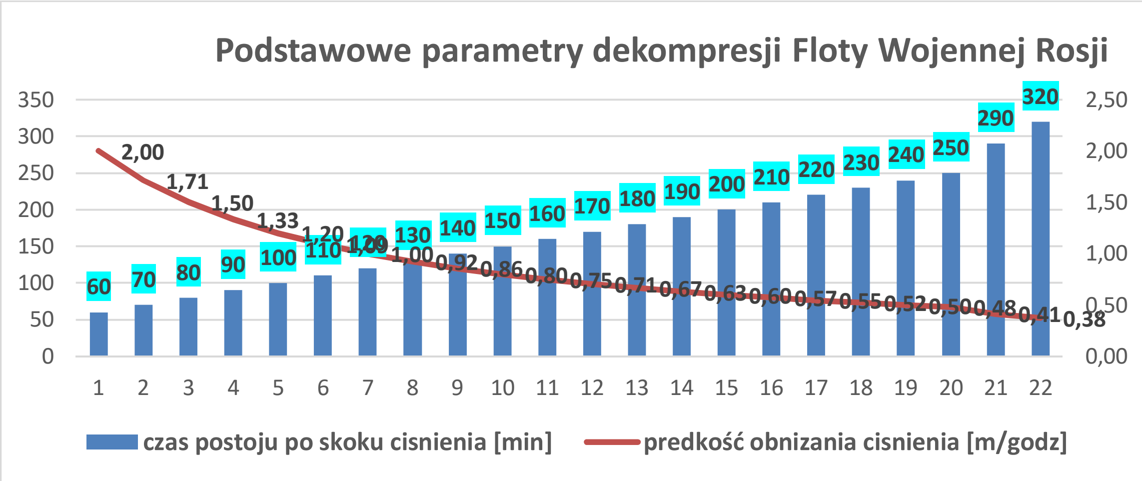

Fig. 10. Stop times after 2m pressure surge and rates of pressure change between intervals.

Tab. 11

Atmosphere parameters at saturation plateau.

Partial pressures	[ata]	Saturation plateau depth [m]
Oxygen pO_2	0,35	300-250m
Oxygen pO_2	0,40	250-150m
Oxygen pO_2	0,50	150-0m
Carbon dioxide pCO_2	0,0025	In the entire range
Nitrogen pN_2	1,60	In the entire range

Tab. 12

Percentage composition of the chamber atmosphere at the saturation plateau for the depth of the Polish shelf.

Saturation plateau	% O_2	% N_2	%He	Typical stopping times	Total decompression time [h:min]
60m	7,1	23	69,90	*11*	54:30
70m	6,3	20	74,75	*8*	66:36
80m	5,6	18	76,40	*7*	77:32

CONTENTS OF HARMFUL ADMIXTURES

Regardless of pressure, the carbon monoxide content in the chamber should not exceed 5 mg/m3 and the total hydrocarbon content converted to carbon should not exceed 50 mg/m3, the relative humidity should be 40-60% as in all other tables.

POLISH SYSTEM OF SATURATION DIVING

The Polish system of saturation diving is the result of research and implementation of remote tests on GWK -200 diving complexes in 1986 - 1991 and then in 1995 modernization of the tables was prepared for the needs of the Navy executing dives of the Petrobaltic company [7,10,16,20].

The Polish system designed for a saturation plateau from 30 to 100m provided for the plateau to maintain a trimix atmosphere with the following parameters:

Oxygen partial pressure $pO_2 = 40$ kPa ± 2;

Nitrogen partial pressure $pN_2 \leq 80$ kPa ± 4 ;

Helium partial pressure pHe ≈ value complementary to the pressure at the saturation plateau

Carbon dioxide partial pressure $pCO_2 \leq 0,3$ % equivalent;

Temperature 28-30ºC ± 1; dependent on the pressure of the carbonation plateau;

Relative humidity 40-60%, mixture movement ≤ 15 cm/sec;

noise ≤ 70 dB/A/, short term 100 dB/A;

microorganisms xx/ to 350 col/m^3 in the absence of pathogenic flora.

Volatile chemical compounds below DNS (harmful agent limit values).

That data indicates that conditions in all the diving systems considered were very similar or identical. Furthermore, by defining the tables as trimix in which $pN_2 \leq 80$ kPa ± 4 is as in atmospheric air, it is a matter of semantics. Virtually all compressions in saturation dives start with the chamber and bell being filled with air, and in the later operations of maintaining of the pressure and composition of the atmosphere and bell when using heliox mixtures the nitrogen content decreases, even though at the sluicing the sluice is also filled with air.

Decompression is carried out continuously with varying rates of pressure reduction. Three hours before it starts, the partial pressure of oxygen in the breathing mixture is raised from 40 kPa to 50 kPa. This is a high-rate depressurisation start; creating a 'suction pulse' gradient. The first 5m is done at rates of 12, 10, 6.7 and 5m/h with a duration of 50-60 min.

Tab. 14

Selected decompression parameters of the Polish saturation diving system.

Depth zone	Oxygen	Carbon dioxide	Nitrogen
Saturation plateau 3 hours	40 kPa to 50 kPa	≤ 0,.3 kPa	≤ 80 kPa
Decompression 100 - 14 m	50kPa	≤ 0,.3 kPa	≤ 80 kPa
Decompression 14 - 0mm	22 % ± 0.8	≤ 0,.3 kPa	≤ 80 kPa

Tab. 15

Percentage composition of the chamber atmosphere maintained at the saturation plateau for the depth of the Polish shelf.

Saturation plateau	% O_2	% N_2	%He	Number of typical stops	Total decompression time [h :min]
60m	7,1	11,5	81,6	*34*	68:41
70m	6,3	10,1	83,6	*34*	78:13
80m	5,6	8,8	85,6	*36*	86:27

As emergency mixtures for therapeutic recompression, from a depth of 100 m to a depth of 50 m a heliox mixture was assumed with 6% O_2 from 50 m to the surface a heliox mixture with 20% O_2. From 18 m to the surface there should also be the possibility of breathing pure oxygen.

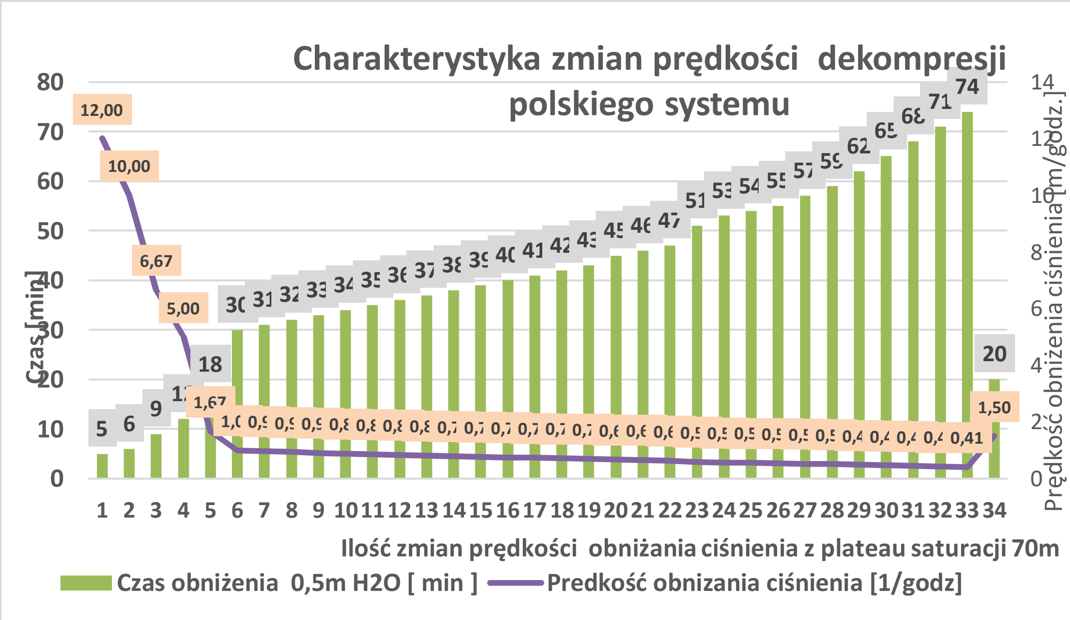

Fig. 11 Continuous pressure reduction times in 0.5m steps of the Polish decompression table system.

Rys. 11 Czasy ciągłych obniżenia ciśnienia w w skokach 0,5m polskiego systemu tabel dekompresyjnych.

In 1995, the trimix saturation decompression system DSK 95 for the Petrobaltic platform diving medical protection system was modified with regard to the composition of the breathing mixture:

- for saturation plateau of 70m: O_2 - 5% - N_2 41% - He 54,0%,
- for saturation plateau of 80m O_2 - 4.4%, N_2 - 40.6%, He - 55.0%.

The above parameters indicate that the tables are for trimix dives and the nitrogen partial pressure during the dive is 3.6 ata which is the original solution. The tables use one pressure reduction rate; from plateau depth to 9m the rate is 0.72 m/h. Unfortunately, these tables have not been validated, primarily for financial reasons, but also for operational and formal reasons.

Tab. 16

Decompression depressurisation rates at the beginning and end of decompression.

DEPTH [m]	TIME min	TOTAL TIME			
70		0 min	=	0 h0 min	
69.5	2	2 min	=	0 h	2 min
69	3	5 min	=	0 h	5 min
68.5	3	8 min	=	0 h	8 min
68	4	12 min	=	0 h	12 min
67.5	4	16 min	=	0 h	16 min
67	4	20 min	=	0 h	20 min
66.5	10	30 min	=	0 h	30 min
66	15	45 min	=	0 h	45 min
65.5	25	70 min	=	1 h	10 min
65	42	112 min	=	1 h	52 min
64.5	42	154 min	=	2 h	34 min
64	42	196 min	=	3 h	16 min
63.5	42	238 min	=	3 h	58 min
63	42	280 min	=	4 h	40 min
62.5	42	322 min	=	5 h	22 min
62	42	364 min	=	6 h	4 min
61.5	42	406 min	=	6 h	46 min
61	42	448 min	=	7 h	28 min
60.5	42	490 min	=	8 h	10 min
60	42	532 min	=	8 h	52 min
9.5	42	4774 min	=	79 h	34 min

9	43	4817 min	=	80 h	17 min
8.5	44	4861 min	=	81 h	1 min
8	45	4906 min	=	81 h	46 min
7.5	47	4953 min	=	82 h	33 min
7	48	5001 min	=	83 h	21 min
6.5	50	5051 min	=	84 h	11 min
6	51	5102 min	=	85 h	2 min
5.5	53	5155 min	=	85 h	55 min
5	54	5209 min	=	86 h	49 min
4.5	56	5265 min	=	87 h	45 min
4	58	5323 min	=	88 h	43 min
3.5	60	5383 min	=	89 h	43 min
3	63	5446 min	=	90 h	46 min
2.5	65	5511 min	=	91 h	51min
2	68	5579 min	=	92 h	59 min
1.5	71	5650 min	=	94 h	10 min
1	74	5724 min	=	95 h	24 min
0.5	20	5744 min	=	95 h	44 min
0		5744 min	=	95 h	44 min

According to DSK 95, the following breathing mixtures are required for diving works from a platform at a depth of 80 meters using a diving bell and hyperbaric chamber (according to US Navy DDC-PTC).:
1. in the chamber: trimix mixes, oxygen,
2. in the bell: trimix (for breathing apparatuses),
3. in individual breathing circuits in the bell from 25% O_2, bell, oxygen.

Tab. 17

Hyperbaric chamber mixture data.

Saturation plateau	pO_2	$\%O_2$	pN_2	$\%N_2$	pHe	%He
70 m (8 ata)	0.46	5.75	3.26	40.75	4.27	53.40
80 m (9 ata)	0.5	5.55	3.61	40.11	4.88	54.22
70 m (8 ata)	0.4	5.0	3.29	41.1	4.3	53.8
80 m (9 ata)	0.4	4.5	3.65	40.5	4.94	54.9

Tab. 18

Data of bell and diver working mixtures.

Working depth of the bell	pO_2	$\%O_2$	pN_2	$\%N_2$	pHe	%He
70 m (8 ata)	0.8	10.0	3.2	40.0	4.0	50.0
80 m (9 ata)	0.9	10.0	3.2	40.0	4.5	50.0

In the second part of the article we will present the criteria for the selection of the tables for operational saturation diving adapted to the modern level of technical and medical knowledge.

REFERENCES

1. Skrzyński S., Pawlak J., Wiśniewski S. “Technologia Nurkowania Saturowanego w Kompleksie Nurkowym Af-2 Część II Realizacja Nurkowania Saturowanego “AMW 2011;
2. Rozporządzenia Ministra Zdrowia z dnia 17 września 2007 r. w sprawie warunków zdrowotnych wykonywania prac podwodnych;
3. Ch. Cadieux - “Implement NORMAM-15/DMC saturation diving procedures CCO Ltd” 25 December 2022 https://www.diving-rov-specialists.com/index.htm;
4. Doboszyński T., Sićko Z. Kot J.: System Nurkowań Saturowanych z użyciem Trimiksu w Strefie Głębokości 80 metrów dla Platformy Wiertniczej Petrobaltic DSK 95 Akademia Marynarki Wojennej Gdynia 1995;
5. Doboszyński T,. Łokucijewski B,,Wybór optymalnego w warunkach krajowych systemu nurkowania saturowanego do głębokości 120m`` Zakład Medycyny Podwodnej Katedry Medycyny Morskiej WAM Gdynia 1986;
6. Dokumentacja i wyniki pracy NURSAT “Wdrożenie nurkowań saturowanych” Akademia Marynarki Wojennej z lat 2000- 2020;
7. Norsok Standard U-100.Manned Underwater Operations Edition 2, July 2008;
8. Technologia Nurkowania Saturowanego Vol.II Rana Diving & Marine Contractor sri, Saturation Diving DOM-02 Rev 04 Grudzień 2007,
9. U.S. Navy Diving Manual revision 1 July 1981, revision 4, 20 January 1999., revision 5, 15;
10. Doboszyński T,. Łokucijewski B,,Wybór optymalnego w warunkach krajowych systemu nurkowania saturowanego do głębokości 120m`` Zakład Medycyny Podwodnej Katedry Medycyny Morskiej WAM Gdynia 1986;
11. Flook V. Sprawozdanie z Badań 244 “Tabele wycieczkowe w nurkowaniu nasycenia – skutki dekompresji obecna praktyka w Wielkiej Brytanii UNIMED SCIENTIFIC LIMITED 123 Ashgrove Road West Aberdeen AB16 5FA Wielka Brytania 2004;
12. Brazilian Navy Directorate of Ports And Coasts Maritime Authority Norms for Subaqcuatic Activities NORMAM-15/DP NORMAM-15/DPC 1 st Review 2011;
13. Imbert J. P., Balestra C., Fatima Zohra Kiboub F.,Z.: Commercial Divers’ Subjective Evaluation of Saturation https://www.frontiersin.org/journals/psychology/ articles/10.3389/ fpsyg.2018.02774;
14. Skrzyński S. “Techniczne Zabezpieczenie Dekompresji Nurków” rozprawa doktorska Akademia Marynarki Wojennej 2003;
15. Bevan J. The professional Diver`s Handbook”. Sumbex Limited. London 2005 ISBN0950824232;
16. Doboszyński T., Łokuciejewski B: “Tabele dekompresyjne dla trimiksowych nurkowań saturowanych do 120 m. wraz z zasadami rekompresji leczniczej”, CPBR-9.5. “Techniczne, medyczne i prawne problemy długotrwałego przebywania człowieka pod wodą”, Katedra Medycyny Morskiej WAM, Gdynia 1990;
17. Załącznik 6. Wyciąg z rozporządzenia UNI 11366 "Bezpieczeństwo i zdrowie w nurkowaniu hiperbarycznym i komercyjnym" "7.3.12 Decompressione di emergenza";
18. Cadieux Ch. “Reinforce US Navy saturation procedures” - CCO Ltd 10 Jan 2019 ://www.diving-rov-specialists.com/index.htm;
19. Procedura nurkowania saturowanego [ang.] Mc Dermont Wielka Brytania Aberdeen 1993;
20. Skrzyński S., Grzeczka G.: Polskie badania nurkowań saturowanych i ich wdrożenie Cz. II PHR 2022; 2[79]: 27-44, 3[80]: 7-22, 4[81]: 69-92 Studies on Saturation Diving in Poland and Practical Application of Their Findings. Developing a Polish System of Saturation Diving in the 1980s and 1990s **DOI:** 10.2478/phr-2022-0020;
21. https://www.cmkp.edu.pl/wp-content/uploads/2023/03/0701-program-1-.pdf;
22. https://www.cmkp.edu.pl/wp-content/uploads/2023/03/0794-program-1-.pdf;
23. (https://www.ptil.no/en/technical-competence/ explore-technical-subjects.

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