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

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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

The first part of the article discussed the saturation diving technologies in use in the past and, in particular, the decompression tables for such dives. Differences and similarities in the approach to the problems of long-term stay and work of people under increased pressure and breathing different gas mixtures were identified.

Between the world's technologies, those tables that have been used during the saturation dives performed in Poland in the Baltic Sea were discussed in detail, as well as Poland's own achievements in the creation of decompression tables for saturation diving were presented.

Conclusions from the analysis of own experiences to date and of other decompression tables used in the world are presented below to guide the selection of tables for future use in Poland.

BASIS FOR THE SELECTION OF DECOMPRESSION TABLES FOR SATURATION DIVING AT THE CURRENT LEVEL OF KNOWLEDGE

Most of the available information comes from studies of the 1980s-90s and early 2000s. They are based on research carried out with state support. Diving companies have their own information policy and their saturation diving technologies can only be assessed with direct participation. This is due to the following factors:

1. a country's traditions and policy of wide-ranging protection of its own interests and recognition of a particular record of safe underwater operations. This type of activity is considered strategic as evidenced by the deep dives conducted by China and Russia in the last five years. Conducting research that is important to national interests at home and refraining from 'internationalising' the results is a logical course of action.

2. the existing technique for the realisation of saturation diving and the system for their protection on a national and international scale. Analysing the latest IMCA recommendations in particular the amendments made to the existing recommendations of the 21st century, emphasis was placed on the fundamentals of the operation of diving systems and the realisation of the protection of these dives. A weakness of these recommendations is that no consideration is given to the computerisation and development of measurement methods for parameters important to the life and safety of divers, which are also not highlighted in the rules of the classification societies.

3. the history, methodology and results of a country's saturation diving research, resulting in a multitude of tables that also took into account, and often even adopted, the achievements of leading countries.

4. analyses of accidents and emergencies by national diving safety authorities,

5. research in physiology and underwater medicine and medical security concerning the long-term stay of people under pressure, the health of saturation divers with many years of experience, the near and distant effects on divers' health and their work fitness. Unfortunately, in the 21st century, research on saturation diving including decompression is mainly oriented towards improving the safety and ergonomics of performing operational dives. Our country used to have experienced military medical personnel, who have now either passed away or are receding into the darkness of history. There is a lack of successors and opportunities to conduct research, especially in terms of funding, which results in a lack of a proper long-term scientific and research policy and the achievements to date being forgotten.

6. This is particularly important as the Polish regulations require the presence of a doctor at the site of saturation dives without specifying his/her responsibilities in the execution of these dives. Moreover, in an absurd manner, they arbitrarily indicate the medical specialisation of said doctor; which does not include any elements of diving and hyperbaric medicine in the specialisation programme [21], and omit doctors with specialisations dedicated to such responsibilities [22]. They therefore rightly reduce their role to research and the provision of so-called 'medical security'. In most saturation diving countries, on-site medical support is provided by the dive leader and the trained team. A delegated doctor secures the dives on land. This is financially sound, as it is cheaper, but the presence of a suitably qualified and doctor prepared to work under pressure on site not only has a positive effect on the well-being of the divers, but also significantly reduces the time taken to provide qualified assistance.

7. acceptance by the ordering party for underwater services; the ordering party is interested in the cheapest and shortest possible execution time with a high level of safety. However, these are mutually exclusive requirements.

COMPARISON OF THE IMPLEMENTATION OF SELECTED SATURATION DIVING TABLES

The depth range of the saturation plateau is between 40 and 90m for the underwater works currently being carried out in our country, and various tables have been considered for planning underwater works for these zones. The main factors considered, apart from safety, are the diver's working depth and the length of the decompression process for which the saturation plateau is selected. The diver's time on the plateau is standard in all countries except Norway and is 28 days, including compression and decompression times and the break time after the last excursion to the start of decompression. Effective diver working time will be the norm of 8 hours in the submerged bell including 4 hours in the water. In addition, the time will be organic compression, decompression and breaks after excursions essential for starting decompression from the saturation plateau. As a general rule, decompression from working depths at the saturation plateau is avoided. Table 19 summarises the main characteristics of the selected tables, indicating decompression durations and breaks and the conditions of the main oxygen partial pressure parameter, and indicating the norms for implementing the depressurisation.

This table references eight tables that use heliox mixes and two that use trimix mixes. The trimix tables are tables that were dedicated to cooperation or offered to the Soviet Union and are the encapsulation of the full deep-sea diving system currently used in Russia. In the rest of the world, heliox is used for saturation dives. The trimix table system is an intermediate system between saturation dives using nitrox and tables using heliox.

Heliox tables are superior to trimix tables in practically all aspects from the execution and their logistical support, the technique used, the complexity of the physiology and pathophysiology of the dive. From the point of view of the composition of the atmosphere of the diving bell and the hyperbaric chamber, at the saturation plateau nitrogen is present with a partial pressure equivalent to that of atmospheric air (and this is due to the fact that both hyperbaric facilities contain atmospheric air at the start of the compression), i.e. the mixture is a three-component mix, although the content of the third component (nitrogen) is of negligible value.

No one, as was suggested to us domestically, ventilates the chamber or bell with heliox prior to the start of compression. (The definition of trimix is referred to here). Over time, due to chamber handling, the nitrogen content decreases, being flushed out with heliox, although each sluicing operation also provides a certain volume of nitrogen.

When using helium recovery systems, with the high price of this gas, the economic argument of using trimix is not considered. It may only be factored in when open-circuit diving breathing equipment is used, during which the mixture inhaled by the diver is ejected into the environment, i.e. lost irretrievably

Tab. 19

Comparison of basic parameters of selected saturation dive tables for saturation plateau at 60, 70 and 80 m..

No.	Selected decompression tables	Total depressurisation time [h:min]	Decompression interval time [h:min]	Total decompression time [h:min]	Oxygen partial pressure chamber [ata]	Oxygen partial pressure bell [ata]	Downward excursion depth [m]	Upward excursion depth [m]	Decompression type
	Saturation plateau at 60m								
	1	3	4	5	6	7	8	9	10
1	US Navy	48;57	18h	66;57	0.44-0.48 ata	0.40-0.60	83.2m	39.7m	continuous or staged
2	RANA 2007	49;54	12h	62;54	0.44-0.48 ata	0.40-0.60	83m	39.7m	continuous
3	Comex	58;27	no breaks	58;27	0.6 ata	0.60-0.80	90m	-	continuous
4	US Navy Standard	**83;53**	40.00	**123;51**	0.49ata	0.6ata	83.2m	39.7m	continuous or staged
5	NORSOK Norway	60;00	18.00	78;00	0.50ata	0.6ata	69m	51m	continuous
6	HSE Great Britain	60;00	10.00	70.00	0.5ata	0.5ata	70mm	62m	continuous
7	Russian Navy	54;30	no breaks	**54;30**	0.50ata	0.6ata	70mm	50m	staged
8	DSK Poland 1995	**86;22**	no breaks	86;22	0.50ata	0.6ata	70mm	50m	continuous
9	NORMAM-15/DPC	62;39	no breaks	62;39	0.50ata	0.6ata	69mm [78]	51m [42m]	continuous or staged
10	CIRIA Great Britain	70;00	no breaks	70;00	0.5ata	0.5ata	70mm	-	staged
	Saturation plateau at 70m								
1	US Navy	54;51	24h	78;51	0.44-0.48 ata	0.40-0.60	95.2m	48.8m	continuous or staged
2	RANA 2007	53;56	12h	65;56	0.44-0.48 ata	0.40-0.60	95.2m	48.8m	continuous
3	Comex	65;20	no breaks	65;20	0.6 ata	0.60-0.80	100m	-	continuous
4	US Navy Standard	**90;59**	42.00	**132;59**	0.49ata	0.6ata	95.2m	48.8m	continuous or staged

Tab. 19 cont

Comparison of basic parameters of selected saturation dive tables for saturation plateau at 60, 70 and 80 m.

5	NORSOK	66;44	18.00	84;44	0.50ata	0.6ata	79m	61m	continuous
6	HSE Great Britain	66;40	12;00	78;40	0.5ata	0.5ata	80m	71m	continuous
7	Russian Navy	66;36	no breaks	**66;36**	0.50ata	0.6ata	80m	60m	staged
8	DSK Poland 1995	**95;44**	no breaks	**95;44**	0.50ata	0.5ata	80m	60m	continuous
9	NORMAM-15/DPC	71;15	no breaks	71;15	0.50ata	0.6ata	79m [88]	61 m[52]	continuous or staged
10	CIRIA Great Britain	77;00	no breaks	77;00	0.5ata	0.5ata	80m	-	staged
	Saturation plateau at 80m								
	1	3	4	5		6	7	8	9
1	Tabela US Navy	**60;10**	26h.	86;10	0.44-0.48	0.40-0.60	105.5m	56.7m	continuous or staged
2	RANA 2007	**59;39**	14h.	73;39	0.44-0.48	0.40-0.60	105.5m	56.7m	continuous
3	Comex	**73;26**	no breaks	73;26	0.6 ata	0.60-0.80	110m	-	-
4	US Navy Standard	**98;55**	42.00	**140;55**	0.49ata	0.6ata	105.5m	56.7m	continuous or staged
5	NORSOK	**73;16**	18.00	91;16	0.50ata	0.6ata	90m	70m	continuous
6	HSE Great Britain	**73;20**	12.00	85;20	0.5ata	0.5ata	98m	70m	continuous
7	Russian Navy	**77;32**	no breaks	77;32	0.50ata	0.6ata	92m	70m	staged
8	DSK Poland 1995	**109;12**	no breaks	**109;12**	0.50ata	0.5ata	90m	70m	continuous
9	NORMAM-15/DPC	**79;51**	no breaks	79;51	0.50ata	0.6ata	90m [100]	70m [60m]	continuous or staged
10	CIRIA Great Britain	**80;00**	no breaks	80;00	0.5ata	0.5ata	90m	-	staged

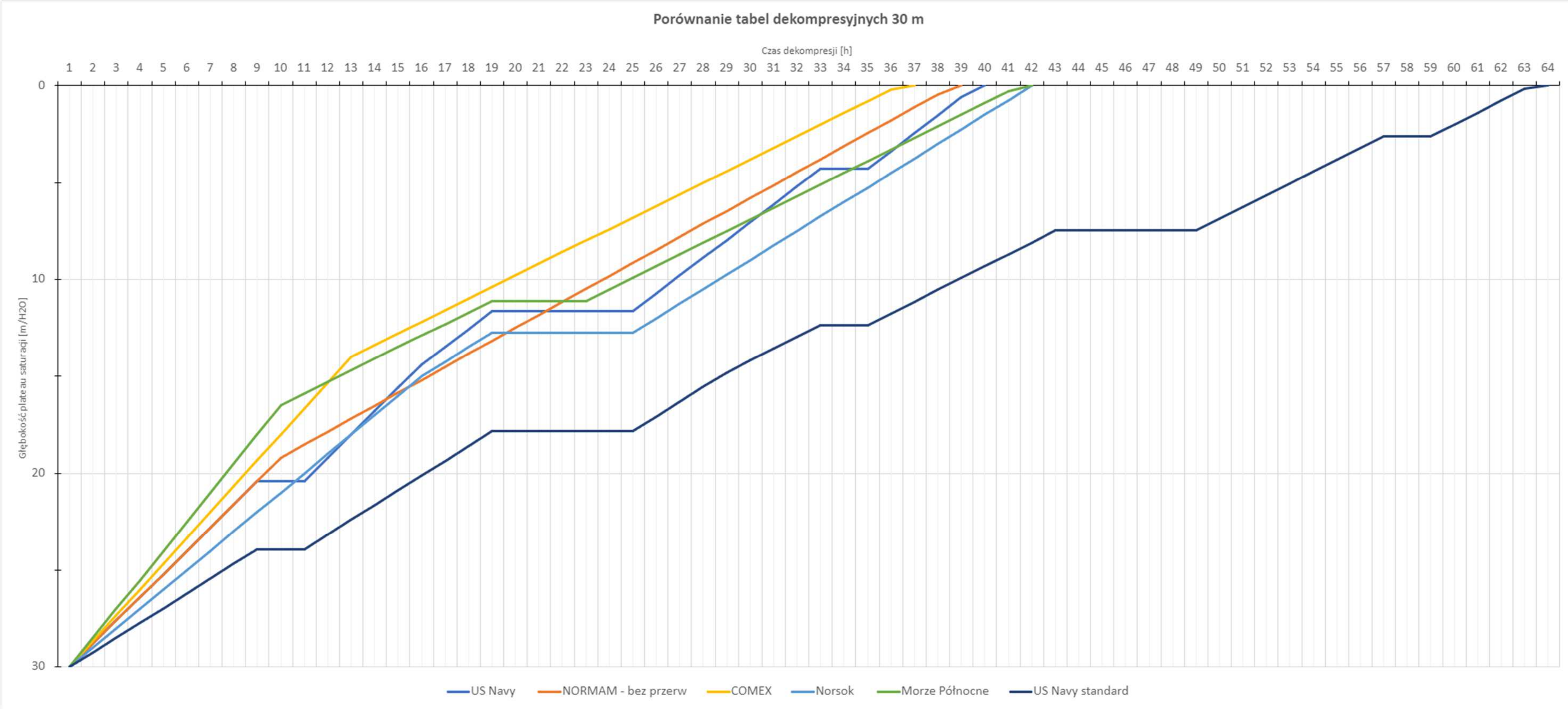

Fig. 12 .Comparison of decompression times of saturation dives from selected decompression tables for a plateau at 30m.

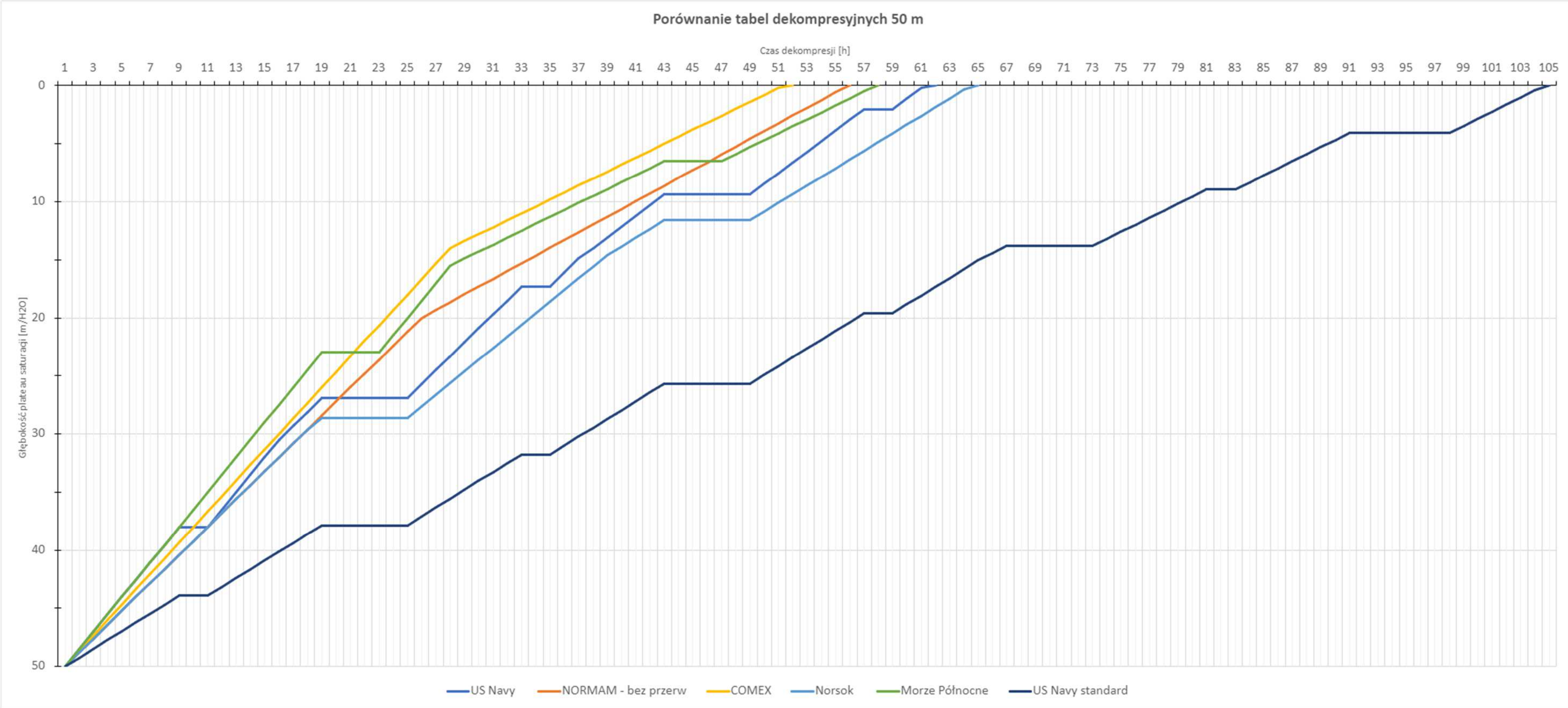

Fig. 12 Comparison of decompression times of saturation dives from selected decompression tables for a plateau at 50m.

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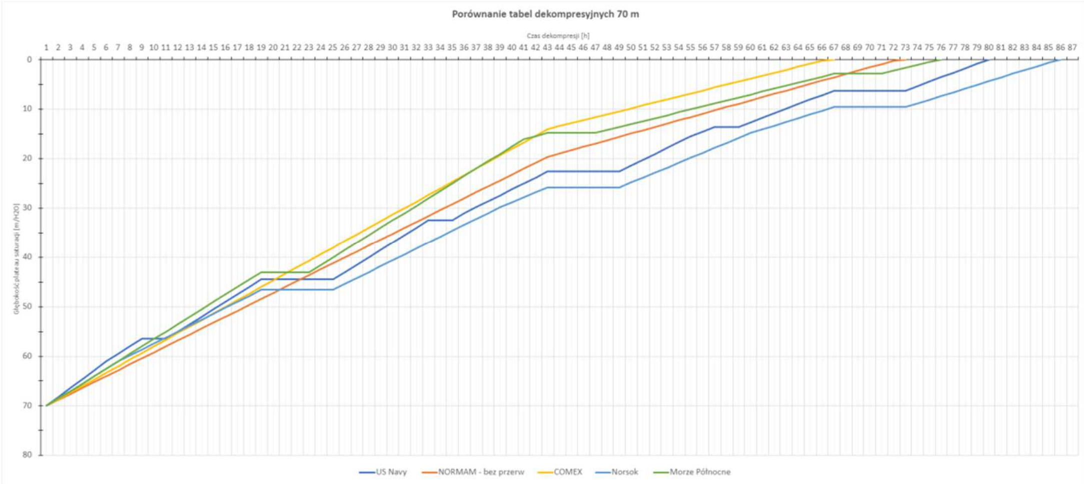

Fig. 14 Comparison of decompression times of saturation dives from selected decompression tables for a plateau at 70m.

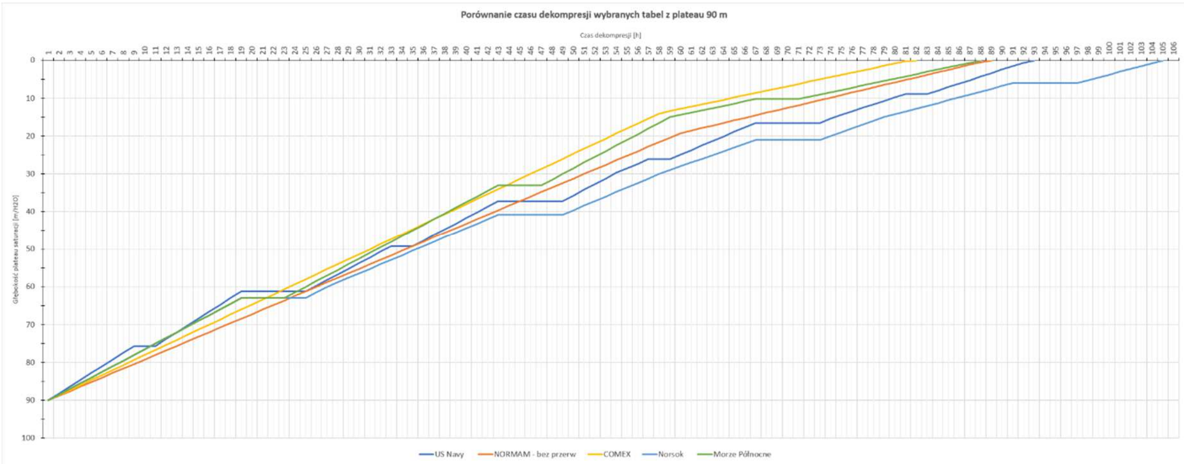

Fig. 15 . Comparison of decompression times of saturation dives from selected decompression tables for a plateau at 90m.

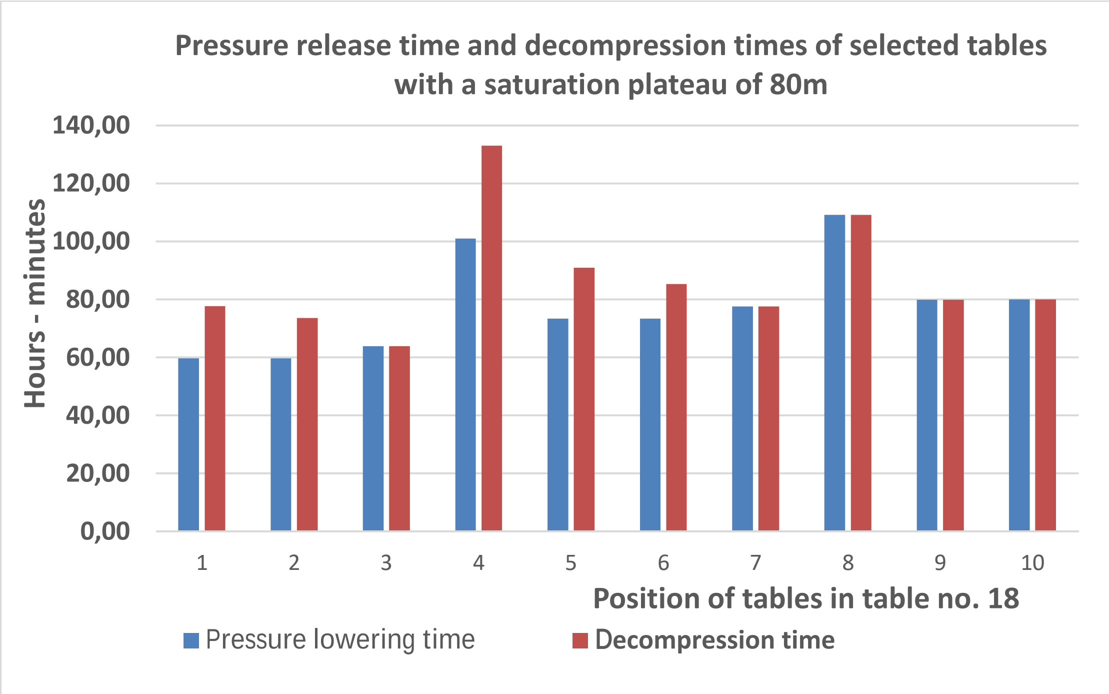

Fig. 16 Diagram of decompression duration including depressurisation times of decompression length with the use of breaks.

Decompression times from saturation plateau

Saturation decompression time - physiological considerations

It is understood that decompression, as the final phase of the diving process, should ensure the safe return of divers to life at atmospheric pressure and breathing air. During decompression, the dissolved inert gases nitrogen and helium in the tissues are removed from the body, with the circulatory and respiratory systems playing a leading role. The process of gas evacuation should be a strictly controllable process through the use of an appropriate depressurisation method, the right composition of breathing atmosphere, conditions of comfort and hygiene of the divers stay under pressure so as to prevent the appearance of bubbles in any of the body tissues. The baseline factor for safe decompression is the diver's health including, but not limited to, proper cardiovascular and respiratory function in the broad sense. To simplify the process leaving aside the cellular level, the first stage is the transfer of gas from the tissues to the venous blood, the second from the venous blood to the alveoli and the third from the alveoli to the environment. Due to the difference in the pressure of the inert gas in the tissues and the incoming blood (pressure gradient), the gas dissolves lowering the pressure in the tissues and this process of moving the inert gas out of the body continues for many hours after the decompression is complete. The selection of a safe pressure gradient at each stage of exchange will determine the decompression time. Naturally, the above-mentioned process is a gross oversimplification, as both the cellular stage and the composition of the blood or even the morphological characteristics of the lungs are important for the rate of saturation and desaturation. In saturation dives, we operate with very low gradients of pressure reduction, which should prevent the formation of gas bubbles that are responsible for decompression incidents. In other words, since all decompression models are only mathematical approximations of organismal functions and no two organisms are identical, the widest possible safety margin is applied.

The evacuation of inert gas during decompression is also assisted by proper hydration of the body, and a diet that does not burden the circulatory system or generate hyperlipidaemia and hypercholesterolaemia in the blood. The set-up of hydration and diet for divers should be individual, because of the different reactions of divers' bodies. In saturation diving, as opposed to short-term diving, we generally do not take into account the anthropometric conditions of the divers. In years gone by, the requirements for a diver were a height of up to 175 cm and a weight of 72 kg. In our practice, admittedly rarely, divers of about 100 kg and height under 185 cm have been involved in dives. If the technical conditions of the chamber, bell etc. allow people of greater (or lesser) height to perform work, they may be qualified to work in saturation. In saturation dives we use one decompression for all divers.

Decompression model selection for saturation dives

All of the tables cited earlier were verified and validated against the health safety and decompression incident risk assessment of the decompression model used. However, the following factors remain known but not considered:
- the remote effects of saturation diving, the medical literature available does not contain many descriptions of

this issue, however, it is known that, like other types of diving, it is not indifferent to health,
- the technical and organisational conditions under which the verified decompression tables were verified (medical and technical measurement methodology),
- a selected group of experimental divers subjected to complex medical tests. The problem is important if, when verifying the tables, we do not take divers with greater capabilities and with some 'baggage' of the impact of diving. The best solution would be to involve non-divers in the verification of the tables, in order to distinguish possible illnesses in the diver's later life. However, this is unrealistic from the point of view of the current research ethics in European countries and the USA. The authors suspect, although they have no evidence of this, that in countries such as Russia or China, where the approach to the problem of research involving human subjects is different, such experiments are conducted.
- statistical approach methodology with appropriate confidence intervals. Verifications of saturation dive tables are based on a sample small group of experimental divers. Statistical inference is also based on a certain model that is chosen. Validation is confirmation that certain requirements for a specific use have been met and implies proof of decompression quality. The main indicator is the absence of a decompression incident supplemented by physiological tests, especially tests that can visualise in real time the presence of gas bubbles in the tissues. Our assessment is that there is no objective, standardised approach to this problem.

Operational factors affecting decompression time

The main factor influencing decompression length for the table used is the saturation plateau depth and indirectly the oxygen partial pressure setting, which are strictly defined in the tables in question. In the tables analysed, the decompression times at the same saturation plateau are different for two reasons: firstly, the different rates of pressure change, decompression start and finish, and the use of breaks. In the practice of operational saturation dives, intervals of 6 hours and 8 hours were used at similar or the same rates of depressurisation. Decompression durations for the depth zones considered range from 2 to 5 days. The differences in decompression times for selected tables and the quoted saturation plateaus for the Polish Baltic conditions are considerable and in extreme cases amount to some tens of hours.

In the tables quoted, rest breaks are used during decompression, as in the US Navy [9], which apply over a 24-hour period. In our opinion, the rest breaks also have a stabilising, compensating effect on the body's state of saturation (decompression stress), particularly concerning the so-called free tissues, which improves decompression safety.

In the practice of saturation diving, intervals of 4, 6 and 8 h are used. These lengthen the decompression by e.g. 8 h. on a 24-hour scale. Thus, in the case of a decompression duration of 3 days, the decompression length increases by another 24 h with the appropriate decompression start setting. We have illustrated the differences in decompression times of selected tables in the diagrams. For the NORMAM system, the difference between the used system and the modified interval system is shown.

Decompression in countries with year-round saturation dives is usually carried out in two phases. It starts with a pO_2 constant for the chamber (50 hPa in the UK, 48 hPa in Norway) up to 15 mwc and ends with a percentage of oxygen in the chamber between 23.1 and 23% to reduce the risk of fire and optimise inert gas exhalation.

From a diver's health point of view, the length of decompression is what makes it safer. In the longest decompression, the decompression time is equal to double the time of any other decompression. (US Navy Standard – COMEX). Otherwise, the length of decompression time approaches that of the proposed emergency accelerated decompression. (US Navy Standard – US Navy and others).

In our modest practice of saturation diving, we have used extended decompression times resulting from the tables used, based on the US Navy from the 1980s and the 21st century. It should also be noted, as already mentioned, that the length of decompression also depends on the setting of breaks, which is related to the start time of decompression and the second condition that we do not use breaks in the final phase of decompression at depths of less than 3 m.

Control of oxygen partial pressure during decompression

In our 30 years of operational saturation diving practice, oxygen partial pressures of 0.35 to 0.45ata were maintained at the saturation plateau using decompression tables based on US Navy tables (which record oxygen partial pressures of 0.48 - 0.5ata). In Polish technology, the pressure was lowered for 4 h prior to the start. Before, the oxygen partial pressure was raised to 0.5 ata using isobaric decompression. From the data shown in the tables comparing the individual tables for saturation dives, it is evident that all tables use oxygen partial pressure increases of 0.5±0.2 ata during decompression. The exception is COMEX where an optional partial pressure of 0.6 ata±0.25 ata for plateau depths is used for underwater works on the Polish shelf.

All decompression tables 'slow down' in the 15 - 20m zone due to the safe oxygen content of the chamber's atmosphere set at 21-23%.

Dilemmas for the future of decompression selection for saturation diving in Poland

Decompression tables in a wide range of commercial, recreational and military application dives are a fundamental and essential element that until just over three decades ago were still treated as taboo. Research and development of decompression and the possibilities of computerisation have resulted in a wide range of approaches to the process. Nowadays, any diver can use the Internet to select decompression and set it to suit his or her needs and abilities. Or at least that is what they think …. Despite the widespread use of personal dive computers in commercial and military diving, strict formalisation of the decompression procedure is mandatory due to organisational requirements, supervision, degree of risk of underwater tasks and insurance claims. When implementing decompression tables, the diver takes full responsibility for the procedures used including decompression procedures.

The selection of decompression tables and the technical provision of decompression, especially in saturation diving, has a different dimension, incomparable to commercial short-duration diving, if only because of a number of technical and organisational requirements for which high financial investments are made to meet the conditions for ensuring the health and life safety of the diver. These requirements are being modernised both nationally and internationally, as with the current economic development of the world it is difficult to imagine offshore activities without saturation diving. From the very beginnings of seabed mining, efforts were made to eliminate saturation diving by introducing diverless technologies, which competed with divers and won decisively only in cases where the depth of extraction was inaccessible to divers for physiological reasons; the diver's ability to work at very high pressures.

Historically, commercial saturation diving was developed in the 1970s for oil rig installations in the North Sea. In those 'early days', when diving in such harsh conditions was not safe, and today continues to be difficult: [13]. Fifty years later, saturation diving procedures have improved significantly and decompression sickness is virtually non-existent. Official safety records published in Norway on the PSA (Petroleum Safety Authority) website indicate an incidence of less than one case per 2,000 dives over the past 10 years [23]. On the other hand, there emerged a need to assess the health and decompression stress of divers in order to improve the norms of saturation diving (e.g. minimum dive intervals, optimal oxygen partial pressure, stay time at the saturation plateau, etc.).

In modernising the saturation diving system in our country, we are given a choice between two routes.

The first - to build on previous experience and implement the research and experience of a selected country where saturation diving is an everyday occurrence. Based on information from specialists dealing with this issue, the number of hours a diving team spends under pressure during underwater works in the North Sea is several thousand, which gives a few dozen hours of diving for a group of several hundred people per year. It provides the possibility for a reliable statistical evaluation of the research and thus an assessment of the impact of carrying out such work on divers' health. It also makes it possible to correlate the existing norms of saturation diving. Our experience is several hundred hours per year for a group of around a dozen divers. For Polish divers working in our country saturation diving is not an everyday occurrence, but an exception in active professional work, requiring a separate approach to the system in comparison with saturation divers working systematically. The Polish experience shows that a diver working at shallow to medium depths on a daily basis using bounce diving also works well in saturation diving.

The second route - the selection and adoption of a new decompression system with its determinants. This undertaking should take into account the technology at hand and the stakeholders, which are the offshore industry, offshore wind energy and the Navy. The participation of these three stakeholders would require agreement on the distribution of financial and in-kind inputs. Access to other countries' safety data and research will be difficult, as, unlike Polish decision-makers, no one in the world is interested in the "internationalization", especially free of charge, of their own output, and international consortia "rule" the seas in saturation diving. We believe that these consortia may not be interested in the niche market of underwater works like the Baltic Sea. Will they be willing to make their technologies available? We believe that it is not in their interest.

It is important to emphasise that Poland, as a maritime country, needs to have a saturation diving capability available, due to defence and economic interests.

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