POLISH STUDIES ON SATURATION DIVING AND PRACTICAL APPLICATION OF THEIR FINDINGS. PART III A
TECHNICAL AND ORGANISATIONAL ISSUES OF THE IMPLEMENTATION OF SATURATION DIVING IN POLAND FROM THE 1990S ONWARDS. PART 1

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ABSTRACT

This article is another in a series of articles on the research and implementation of saturation diving technology in Poland. It discusses the specificities related to the implementation of this technology against the background of economic and historical conditions in our country. In Poland, the issue of saturation diving for the needs of the emerging offshore mining industry has been for over a dozen years dealt with by the Department of Diving Equipment and Technology of Underwater Works (Polish abbr. ZSNiTPP). In parallel, deep diving technologies were developed, in the first stage, as a basic diving technology and, since 1994, as complementary to ensure the full backup for saturation diving. Since 1995, saturation diving has become an everyday occurrence in the Polish economic zone of the Baltic Sea. This article shows the difficult path that the implementation of saturation diving took during a period of economic instability when the scale of the domestic offshore industry's facilities was small compared to global companies. Selected animators and participants in the implementation are recalled for two periods: one marked with the cooperation with the Italian underwater services company RANA and the other one, a period of implementation of long-term underwater works based on national capabilities. The article also considers the technical and organisational conditions for the implementation of saturation diving for the Polish mining industry. In 1990, the Oil and Gas Exploration and Production Company Petrobaltic (today LOTOS) played one of the key roles in the implementation of saturation diving in our country. The implementation of saturation diving in Poland was linked to the only operational diving system of Italian production, the Af-2, which enabled scientific research related to the application of new technical solutions and testing under operational conditions, as well as contributed to the development of scientific, engineering, and medical staff for the Polish offshore industry. The company played one of the main roles in the implementation of saturation diving in our country The 1995 became a landmark year in the history of saturation diving in Poland, as well as in the Baltic Sea. Through this technology, the process of installing the first two underwater exploitation heads on production wells B3-7 and B3-10 was initiated. The saturation diving was possible thanks to the leasing of the Af-2 diving system by Petrobaltic and its subsequent purchase by the Naval Academy in 1998.This system, after a series of upgrades, is still in service today.
Keywords:. saturation diving technology, decompression tables, saturation diving parameters, long-term underwater work, diving system, emergencies, technical and organisational backup for diving, medical issues of operational saturation diving, mobile diving system, saturation diving base, breathing mixtures.

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ORIGINS OF THE SUBJECT

The underwater services and works industry is a strategic industry for any maritime country. Our country's economy in the past and even more so in the future will need a strong, independent underwater services base. In the classic definition of underwater work involving divers, scuba diving is the technology that demonstrates the power of a maritime state, in terms of both economic and defence-related aspects. Pure diving draws on three scientific disciplines: medicine, technology, and organisation. Commercial diving, on the other hand, extends this interdisciplinarity and draws on virtually all sciences related to human activity. The spectrum of sciences used in diving and especially in saturation diving is complemented by; economics, psychology, ergonomics, thermodynamics, statistics, metrology, mereology, navigation, computer science, occupational hygiene, defence sciences, etc. The following article demonstrates the range of problems that a group of scientists, production managers, offshore mining, maritime administration, underwater engineering, diving and underwater work specialists in the Polish offshore industry have encountered and continue to encounter. The future in which Poland is to move its power industry on to the sea with unprecedented energy will require knowledge of our country's problems in planning and implementation. These activities also require creative imagination, investment courage and well prepared backup facilities. The whole process should be handled by one leading institution that "feels" and is familiar with Polish reality. The article shows the problems encountered by those who implemented saturation diving in Poland. Future problems of underwater work will be the same, but will take place in a different technical, economic and political context. The authors dedicate this work to future implementers of underwater work, especially to people of science.

BACKGROUND INFORMATION

At the beginning of 1992 it seemed that the results of the saturation diving research carried out in Poland had been irretrievably lost. The indebtedness of the Szczecin Shipyard, which had occurred during the construction of diving systems for the Soviet Union at the Naval Academy, amounted to more than 1.5 times the annual budget of the Academy, according to the Bursar. The Academy's authorities were sceptical but understanding about matters relating to research into the problem of human labour in hypersonic conditions following the failure of government-funded programmes related to this subject. A lengthy process of debt recovery began as part of the yard's debt relief procedures. From 1991 onwards, collective redundancies began at the Department of Diving Equipment and Technology for Underwater Work (ZSNiTPP), which resulted in the workforce being almost halved. At the same time, the administration of the Department was taken over by the administration of the Academy. Despite such negative developments, experience and knowledge were not lost. Thanks to the people of science and the engineering and diving staff, the people who remained on the team, activities began to further implement the knowledge gained in the national economy and for defence purposes. It is also not insignificant that the experience has been and continues to be passed on to the next generation of scientists and technicians involved in diving for military purposes and underwater work. A spectacularly positive development of this path of transferring research experience from 1981 to 1991 is that, since 1993, opportunities have opened up to use the experience gained for the Polish offshore industry.

After the political changes in 1989, a Polish oil and gas exploration and production company was spun off, this time under the same name as the tripartite (Poland, GDR, USSR) Petrobaltic oil exploration and production company. It was not large-scale extraction, but the platforms it owned were and are the country's leading 'mines' for these economically important raw materials. In Poland, this industry was not the driving force behind the development of diving equipment and technology and underwater work technology, as it was in the world, but it laid strong foundations for the launch of domestic diving and underwater work potential.

Petrobaltic had its own urgent needs in starting economically viable production of oil and gas from licensed oil fields at depths of 70-85m. Our country was not prepared to secure work for the needs of the Polish oil industry in the Baltic, even though in the 1980s Poland had spent heavily on developing diving technology intended for export to the former USSR. From 1982 to 1991, intermittently, the Polish Navy performed services for Petrobaltic without the participation of the Polish Naval Academy. On the other hand, between 1992 and 1994, work was performed with and on diving technologies developed at the Department of Diving Equipment and Technology of Underwater Works (Polish abbr. ZSNiTPP). The Polish Navy was the lead contractor and the Department implemented the developed technologies on this occasion. The funds obtained from this work made it possible to secure financing for 80% of the operation of the Department, as it had been self-financing since the work for the Szczecin Shipyard.

When the urgent need for saturation diving arose after the economic reform in 1995, there was no capacity to do the work in Poland. The Navy had one rescue ship with a diving bell adapted for deep dives with helium-oxygen mixtures using FGG-III semi-closed circuit apparatus made by the German company Dräger. These apparatuses were purchased by PETROBALTIC. These dives used the US -Navy deep dive tables, unfortunately, disregarding the peculiarities of the semi-closed circuit apparatus, so these dives were high-risk ones. At the beginning of 1992, for the needs of the extraction industry, deep trimix diving technologies were being prepared in the Department for technical and implementation purposes by modernising the FGG III apparatus and the diving bell and adapting the chamber for oxygen decompression. We were the only country in the world to use this type of diving apparatus for commercial diving. This apparatus, like any semi-closed circuit apparatus, had limitations. The most significant of these was the unstable composition of the breathing mixture when the demand was high, i.e., when the diver was working hard. The decompression tables developed for deep diving technology were used for diving from rescue ships of the Navy for the needs of Petrobaltic until 1997.

CONDITIONS FOR THE IMPLEMENTATION OF UNDERWATER WORKS AT PETROBALTIC

The deposits exploited by Poland are located between 70 and 90 miles from the land base and in a depth zone of 70 - 90m. The distance from the shore and the depth of extraction are the main factors that drive the technical solutions related to the extraction and transport of raw materials, and the support for the work. The main technical problems of underwater work, which are solved for offshore production platforms, concern the transportation systems, the installation of heads for the controlled extraction of oil and gas, and the pipelines through which these resources are transported to the receiver or to the tankers. In addition, so-called underwater maintenance service is required in day-to-day operations, necessary for the exploitation process after the installation of the heads and pipelines. This generally includes maintenance, repairs, inspections and supervision by classification societies and maritime administrations.

SECURING UNDERWATER WORKS IN THE POLISH SHELF BETWEEN 1992 AND 1995

Until 1995, short-duration deep dives were used for underwater inspection work, very small-scale installation work and for ad hoc work by the diver at a working depth of 30 to 45min. Deep diving technology did not allow for installation of underwater structures, at most it could be used as a support for emergency intervention and to complement works using saturation diving.

Many of the world's experts at the time believed that the future of offshore underwater work would rest on systems and technologies based on remotely operated underwater robots and specialised manned vehicles equipped with manipulators. Underwater infrastructure systems are operated remotely by an operator from the surface or directly by the crew of the underwater vehicle. These are either diver-free or operator-assisted technologies where the body is not affected by pressure. At this stage of Petrobaltic's development, these technologies could not even be considered for economic reasons and the mining technology available at the time. Underwater technologies that assume the "absence of divers" were and are currently very costly, and they are mainly used for work where the work of a diver is impossible for physiological reasons. As practice shows, the above-mentioned technologies, despite the fact that they do not provide for divers' work, have to use their services to a limited extent and not only in emergency cases.

Petrobaltic's first underwater assembly and installation work also used simple technologies that did not require the direct involvement of a diver. These were the installation of flexible steel pipelines that do not require welding during installation. During their installation, an underwater camera placed on the pipes (so-called 'siphons') was used, controlled to a limited extent by lashings to observe operations on the drill holes. In the early days of this work, the simplest ROVs were used, of the 'eyeball' type with a TV camera, later retrofitted with a low force manipulator. They were used as stand-alone underwater inspection equipment and/or as a diving support device. These vehicles were controlled and powered from the surface via a cable (umbilical - a word used in marine drillers' slang). Unfortunately, if an ROV-type underwater vehicle became entangled in underwater structures, a diver always had to intervene. During the early days of field operations, ROV cable entanglement was relatively common until the operators of these vehicles were fully trained.

Comparing the effectiveness of the aforementioned diving in domestic practice at the Petrobaltic platform, one diver in saturation diving worked 48 hours underwater at a depth of 80m in 1995, staying under pressure for more than 30 days, including 3 days of decompression. The advancement of the science in diving has not changed to the present day and specifies the recommended working time for a diver for single dives (residence time including immersion) to be 1.5 hours to a maximum of 2 hours with provision for an unplanned extension of the stay on the bottom. This means that when the diver's stay time at the depth specified in the tables for short dives is exceeded, we should use saturation diving [1]. So-called 'subsaturated dives' were practically and theoretically undeveloped and could not be used at Petrobaltic's oil production depths. In contrast, during the whole of 1994, a team of 12 divers using standard diving worked approximately 51 hours during 58 dives during the year, which required more than 312 hours of person-decompression. In standard diving, the length of time a diver stays at a given depth is very strictly limited, and exceeding this limit results in decompression being extended by up to over a dozen of hours. The ratio of the diver's time at depth to the total dive time is one indicator of dive efficiency.

It should be added that there are no regulations for saturation diving in our country. All dives that took place in Poland were carried out as experimental deployment dives [2]. That was and still is possible thanks to the Naval Academy. To date, our country lacks basic formal documents on saturation diving, such as decompression tables.

For the development associated with the construction of Petrobatlic's underwater extraction structures, long-term underwater work, rather than short intervention diving works in the 50-85m depth zone, was necessary. Saturation diving was the only basic technology for the needs of the nascent Polish offshore industry. Saturation diving was essential for underwater installation, repair and maintenance work, which ensured Petrobaltic's growth and economic efficiency. The use of saturation diving forced out changes in the design and modernization of underwater installations. The designs took into account the specifics of these dives, in particular, the possibility of a virtually unlimited number of hours worked by the diver at depth, with high availability, and the independence of decompression time from the number of these hours. Divers staying under pressure from several to over a dozen days work an average of 3 to 6 hours underwater every day without decompression. In short duration dives at the same depths, this is physiologically impossible and economically unviable.

Although the Navy was bound by a contract with Petrobaltic to secure underwater work, it had neither the equipment nor technology that would secure underwater operations related to that company's development. It performed a core element of these obligations through the training of personnel, ensuring technical and shore-related aspects for dives and support for typical anticipated offshore emergencies. While training Navy deep-sea divers, diving personnel from rescue ships and the Navy Diver and Frogman Training Centre at ZSNiTPP, a diving team was simultaneously prepared for saturation dives. Three research saturation exposures were performed in conjunction with the training of this team in DGKN 120 at low saturation plateau depths of 30m. Preparation for the saturation dives also required preparation and expansion of the dive team. This involved expanding the organisational side of implementation of deep-sea diving, which required the training of divers, technical staff and dive leaders, who were in parallel preparing for saturation dives. This was an unprecedented case in Poland in new economic reality where organisations representing industry and defence sectors got engaged in mutually profitable cooperation for the benefit of the country. This cooperation was very helpful in launching the first underwater work using operational saturation diving in the Polish economic zone in the Baltic Sea for the oil production industry in 1995.

In 1994, when there was a real need for assembly-related dives for Petrobaltic, Poland found itself in a paradoxical situation. We had a team for saturation dives, but we did not have the technology and capacity to deploy them operationally in real-life conditions.

When, in 1995, in Poland there was no capacity available in the national market to carry out underwater work, the management of Petrobaltic, and in particular the Operations Director J. Bokiniec, on whom "responsibility for oil production rested" and who was the driving force behind the implementation of commercial deep diving in Poland, decided to look for a saturation diving system abroad. At the time, our country was a research 'superpower' with two shore-based research systems based in the city of Gdynia. It was a base for research and training to secure saturation diving, but had no real operational capability to carry out these dives. One centre with a long tradition and a team of research and medical staff was located at the Naval Academy. The other new one, equipped with a set of LSH -200 chambers manufactured by Szczecin Shipyard, was located at the then Institute of Maritime and Tropical Medicine (Polish abbr. IMMiT). This centre was only at the beginning of its development, with virtually no medical, technical or diving team of its own. As if that were not enough, there were elements of the GWK-200 diving systems left in the Szczecin Shipyard, some of which were purchased for the IMMiT. As late as 2020, elements in the raw state of the GWK-200 system were still seen there, such as, chambers, diving bell, bell lifting system and many others. These basic elements in their raw state 'haunted' in front of the building where the LSH-200 was installed (now a facility of the Gdansk Medical University, Faculty of Health Sciences with the Institute of Maritime and Tropical Medicine). As part of debt reduction, also the Department of Diving Equipment and Underwater Work Technology received elements of the GWK-200 systems, which were closed-circuit diving system installations manufactured by the German Dräger GAK-450, gas and metering components. Most of these equipment and components were used secondarily to build or upgrade the diving systems. The construction of an operational diving system for deep and saturation diving on selected vessels, of which there were relatively many as fishing companies were being liquidated during this period, was planned and designed. That indicated the paradox in our country that the intellectual and research potential, which should have been used for the good of the country when the need arose, was deprived of the possibility to implement the main research results.

Polish decompression tables for operational saturation diving with trimix mixtures

In preparing for operational saturation diving at the ZSNiTPP, based on the results of our own experience, and data from the available literature, it was assessed that the tables developed under CPBR 9 objective 5 should be adapted to the conditions required for underwater work due to:

- variable depressurisation rates in short depth intervals, requiring a specific approach to decompression execution,
- the need to vary the oxygen dosage to maintain the partial pressure required for decompression at variable speeds,
- high measurement precision exceeding that of operational and diving systems,
- decompression durations longer than in available foreign tables,
- standards defining the partial pressure of oxygen in the breathing mixture of a diver working at depth close to the pressure of the saturation plateau, which did not correspond to the requirements of operational diving, in which divers work in a depth zone varying by ±15m. relative to the depth of the saturation plateau. The tables were not tested for acceptable changes in the diver's working depth of so-called 'excursion' relative to the 'decompression horizon' as the saturation plateau was called in the literature,
- developed 'trimix saturation dives' to indicate that during decompression heliox mixture was introduced into a chamber containing air. All heliox tables omit the partial pressure of nitrogen up to 1.2 ata .(corresponding to about 5.5m depth with the use of air). In contrast, the Polish tables developed in 1989 allowed only a partial pressure of nitrogen corresponding to its partial pressure in atmospheric air. pN_2 = 0.78 ata. [3]

As the Navy at that time was using trimix decompression tables for deep diving, which had been developed by the team of the Department of Maritime Medicine of the Military Medical Academy, Prof. Doboszyński was asked to modify the developed decompression tables for saturation diving and adapt them to the requirements of operational diving. It was agreed with Prof. Doboszynski that the modification would take into account the deep trimix diving system used by the Navy. He was the author of the study 'System of Saturation Diving Using Trimix in the 80-metre Depth Zone for the *Petrobaltic* Drilling Platform' DSK - 95. Co-authors added, to our huge surprise, were Z. Sicko and J. Kot, while the names of physicians from the Department of Medicine of the Military Medical Academy, who for many years actively, with great dedication, worked on and verified the decompression tables for saturation dives, and took part in the adoption of trimix decompression tables for deep dives using the diving system of the ORP Lech ship, i.e., the actual co-authors were missing.

In the introductory part, the paper analysed the available decompression tables for saturation diving, including - in the case of Russian and RANA company's – tables officially owned by the Naval Academy's US Navy deck decompression chamber –

Department ZSNiTPP. Five, up-to-date at the time, decompression tables of operational saturation diving systems, allowing several hours of operation each day at depths of 70 - 80 metres in which only heliox mixtures are used, were analysed. A criterion for assessing the medical suitability of individual systems was adopted based on the degree of supersaturation occurring, i.e., the potential occurrence of prerequisites for decompression sickness in the Polish tables used, recognising that in a correct system, decompression from a fully saturated state should not cause critical supersaturation. Only minor, transient functional changes were allowed for the validated model of Polish tables [4].

Validation method for the Polish tables was based on the assumption of dosing decompression loads, moving from permissible tissue supersaturations of smaller to larger tissues in successive exposures. This method allowed a margin of safety to be maintained, taking into account possible errors in the assessment of pO_2 analysis errors, inhomogeneities of the breathing mixture, inaccuracies of the operators and taking into account other disturbances during operational saturation dives. It was assumed that if we can account for the effect of nitrogen on the decompression rate, its presence or absence should not affect its safety.[4]

Parameters of the saturation dive of the DSK - 95 tables using trimix for the saturation plateau of 70 and 80 metres [4]

DSK - 95 addresses selected technical aspects of how dives were executed.

The following breathing mixtures are required for diving works from the platform at a depth of ≈ 80 metres using the saturation technique according to the DDC-PTC method (the term DDC was introduced from the nomenclature of the US Navy deck decompression chamber - base hyperbaric chamber and SDC diving bell submersible decompression chamber):

1. habitat trimix,
2. bell trimix (for supplying the diving apparatus),
3. for individual breathing systems bell-type with 25% O_2, bell-type, oxygen

The preparation of the habitat trimix starting mixture is based on mixing: air 1 parts by volume + nitrogen 1.1 parts by volume + 3.3 parts by volume of helium. Volume percentage of the habitat mixture thus obtained: O_2 - 3.70 %, N_2 - 35.18 %, He - 61.12 %.

Partial pressures of the components of the habitat mixture and their volume percentage together with the partial pressures of the habitat air components at the saturation plateau (directly) after compression.

	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

1.After the reduction of pO_2 in the chamber to 0.4 ata

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

2. Preparation of bell trimix mixture: air 1 part by volume + helium 1 part by volume. Components of bell mixture and their volume percentage:

	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

3. Therapeutical mixture. Preparation of bell trimix mixture with 25% O_2: bell trimix mixture 1 part by volume + oxygen 0.2 parts by volume. Volume percentage of the composition of bell mixture with 25% O_2. Mixture composition O_2 – 25.0 %, N_2 – 33.3 %, He – 41.6 %.

Partial pressure of the components of bell mixture with 25% O_2 and their volume percentage:

	pO_2	$\%O_2$	pN_2	$\%N_2$	pHe	%He
70 m (8 ata)	2.0	25%	2.66	33.3	3.32	41.6
80 m (9 ata)	2.25	25%	2.99	33.3	3.74	41.6

It was recommended that immediately prior to the start of compression with the habitat mixture (mixture at saturation plateau):

- with the regeneration system in the habitat containing air switched on, the divers of the 4-person team connect to "individual breathing systems". From these systems they breathe a bell mixture with increased oxygen content.
- the pressure in the habitat rises at a rate of 2 to 4m/min. When the pressure corresponding to a depth of 30m is reached, compression is stopped. Once it is confirmed that the percentage of oxygen in the atmosphere of the chamber is no more than 7 %, the divers switch individually to breathing the atmosphere of the chamber on the instructions of the dive leader.

Once the intended saturation plateau has been reached, the percentage of oxygen in the habitat breathing mixture should be at p 8 ata ≈ 5.75 %, at p 9 ata ≈ 5.55 %, which corresponds to partial pressures of oxygen of 0.46 and 0.5 respectively, which is higher than recommended. Therefore, the oxygen consumed by the divers is replenished when pO_2 reaches 0.4 ata. The partial pressure of oxygen at the saturation plateau should be maintained with an accuracy of +/- 5% (0.38 - 0.42 ata).

Partial pressure of the components of habitat breathing mixture at the saturation plateau 70 m (8 ata) should be:

pO_2 – 0.4 (5.0%), pN_2 – 3.29 (41.1%), pHe – 4.3 (53.8%)

The density of the mixture corresponds to the density of air at a depth of 32.2 m, the narcotic effect corresponds to air at a depth of 31.1 m. The thermal conductivity of the mixture is more than twice that of the heliox mixture at 70 m.

Partial pressures of the components of habitat breathing mixture at saturation plateau 80 m (9 ata) should be: pO_2 – 0.4 (4.5%), pN_2 – 3.65 (40.6%), pHe – 4.94 (54.9%)

The density of the mixture corresponds to the density of air at a depth of 36.6 m, the narcotic effect corresponds to air at a depth of 35.6 m. The thermal conductivity of the mixture is more than twice lower than the conductivity of the heliox mixture at 80 m.

During the operation of the 2-person team outside the habitat, the bell and the diving apparatus are fed with a bell mixture. It is advisable that the pressure during the diver's work in the depths is close to the pressure in the habitat +/- 6 m, and that the time spent on the plateau is limited to 10 days. After this period with each diver working for 4 hours every day, decompression takes place. Three hours before it starts, the partial pressure of oxygen in the habitat is raised to 0.5 ata. Decompression is carried out according to the attached table (appendix 1 and 2), keeping the pO_2 constant at 0.5 ata. (the "in minus" deviation should not exceed 1%).

From the depth 10.5 m, percentage content of oxygen in the habitat breathing mixture should be 24 %. Decompression time for saturation plateau 70.

Table 1. Example of the initial and final phase of decompression. Trimix saturation decompression system for the system of medical support for diving from the Petrobaltic drilling platform.

Required percentage composition of the breathing mixture at saturation plateau pO_2 4.4% - pN_2 40.6% - pHe 55.0%. 3 hours before the beginning of decompression. The table did not consider breaks in decompression when the divers were sleeping

Tab.1

Example of the initial and final phase of decompression.

DEPTH [m]	**TIME pressure reduction** [min]	**TOTAL TIME {min]=[hour : min]**			
80		0 min	=	0 h	0 min
79.5	2	2 min	=	0 h	2 min
79	3	5 min	=	0 h	5 min
78.5	3	8 min	=	0 h	8 min
78	4	12 min	=	0 h	12 min
77.5	4	16 min	=	0 h	16 min
77	4	20 min	=	0 h	20 min
76.5	10	30 min	=	0 h	30 min
76	15	45 min	=	0 h	45 min
75.5	25	70 min	=	1 h	10 min
75	42	112 min	=	1 h	52 min
74.5	42	154 min	=	2 h	34 min
74	42	196 min	=	3 h	16 min
73.5	42	238 min	=	3 h	58 min
73	42	280 min	=	4 h	40 min
72.5	42	322 min	=	5 h	22 min
72	42	364 min	=	6 h	4 min
71.5	42	406 min	=	6 h	46 min
71	42	448 min	=	7 h	28 min
70.5	42	490 min	=	8 h	10 min
70	42	532 min	=	8 h	52 min
9.5	42	5614 min	=	93 h	34 min

9	42	5656 min	=	94 h	16 min
8.5	43	5699 min	=	94 h	59 min
8	44	5743 min	=	95 h	43 min
7.5	45	5788 min	=	96 h	28 min
7	47	5835 min	=	97 h	15 min
6.5	48	5883 min	=	98 h	3 min
6	50	5933 min	=	98 h	53 min
5.5	51	5984 min	=	99 h	44 min
5	53	6037 min	=	100 h	37 min
4.5	54	6091 min	=	101 h	31 min
4	56	6147 min	=	102 h	27 min
3.5	58	6205 min	=	103 h	25 min
3	60	6265 min	=	104 h	25 min
2.5	63	6328 min	=	105 h	28 min
2	65	6393 min	=	106 h	33 min
1.5	68	6461 min	=	107 h	41 min
1	71	6532 min	=	108 h	52 min
0.5	20	6552 min	=	109 h	12 min
0		6552 min	=	109 h	12 min

Decompression time for saturation plateau 70 m 95 hrs 44min and 109 hrs 12min for 80 m.

The above-mentioned tables are original due to the uniqueness in the world literature of trimix saturation tables for this depth range. They were not practically applicable to operational diving in Polish conditions for the following reasons, apart from the fact that these tables were not practically validated and were verified only on a proven decompression model:

- the tables are provided for a 10-day plateau stay, when the tables used worldwide provided for a 28-day stay including decompression.
- making trimix mixtures in operational conditions of the company and hyperbaric facilities requires multistage mixing, and the accuracy and time to obtain them suffers. These mixtures can be approached as mixing two pure gases, i.e., using air or nitrox with a complex oxygen content mixing with pure helium,
- the additional need to monitor the content of one of the inert gases helium or nitrogen,
- did not take into account the available diving technology, i.e., the large number of pressure vessels and the possibility of pumping them,
- the length of decompression lasting more than 4.5 days, while with the use of heliox the decompression, depending on the tables, can be even 2 days shorter in the 70-75m depth zone of interest to Petrobaltic.

Brief analysis of the then operational modernised decompression tables for saturation diving

In the opinion of the authors and others, any decompression table system should consist of a set of tables providing and specifying the technical and medical safety of the execution of the dives. In saturation dives, the set of tables should be extended due to the definition of the following data:

- dive depth zones in relation to the saturation plateau, (maximum and minimum working depths of the divers and their maximum residence time),
- dive start times after compression to the plateau depth,
- diver working time start after reaching the saturation plateau, (bell immersion – diver's work in water),
- the start time for decompression after the divers have returned from the last dive; the last bell immersion in a given dive.

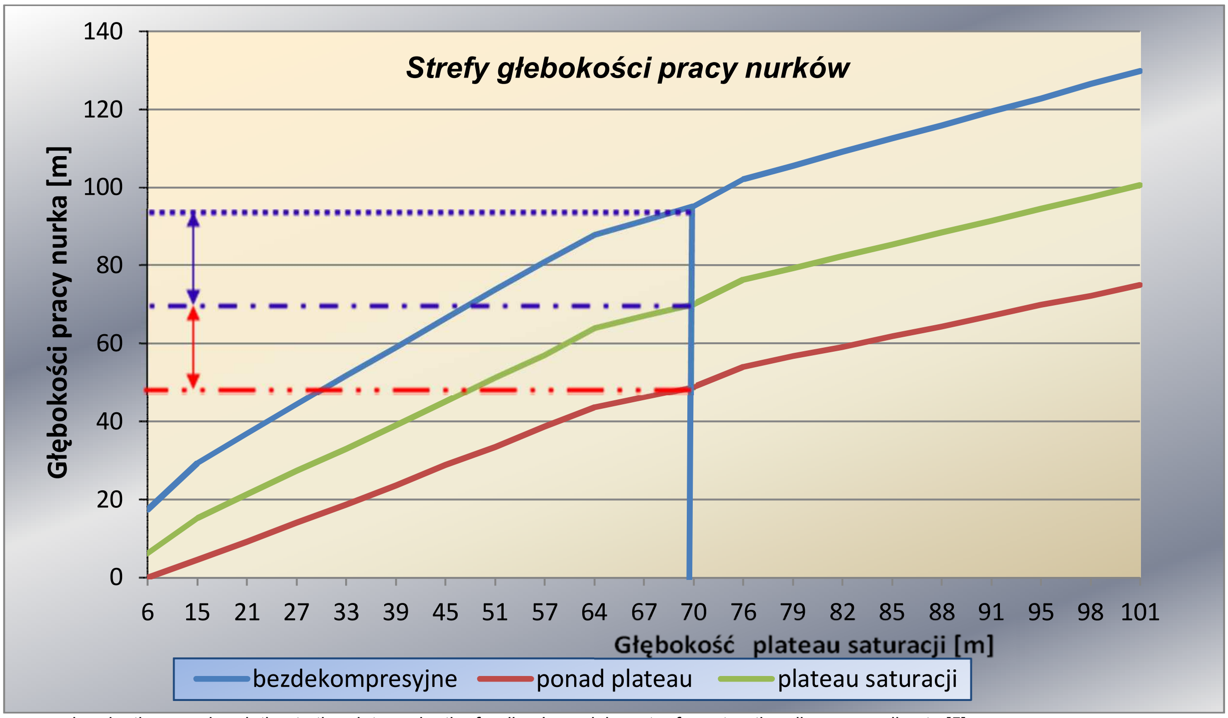

Fig. 1 No-compression depth zones in relation to the plateau depth of a diver's work in water for saturation dives according to [5].

A complete system of decompression tables for saturation diving should include the following tables

- working tables with implementing conditions,
- decompression acceleration tables for emergency conditions including pressurised evacuation procedures ,
- decompression tables with saturation plateau for times beyond non-decompression depths,
- indications for diver operating at depths below the saturation plateau,
- abort tables, usually for deep dives or for long compression times, specially calculated.
- therapeutic recompression tables,

The aforementioned list of tables shows the importance of adapting the implemented tables for saturation diving taking into account the medical team and the safety techniques for which the tables are to be implemented. In validation studies of tables for saturation diving, working tables are checked and technical and medical safety requirements are determined. Other tables are selected or calculated according to an assumed model. For instance, decompression acceleration tables vs. abort tables in the range outside the deep dive tables can be determined by appropriate equivalent depth calculations or by adopting a selected mode of therapeutic recompression. The saturation diving used on the Polish shelf is at the contractual limit of shallow saturation diving at the contractual depth limit depending on the country of 50 - 80m. In the case of a situation where compression is interrupted from a saturation plateau of 100 - 200m and deeper, there are no such broad possibilities and in emergency situations the procedures associated with decompression saturation diving are "kept".

Below, we provide brief characteristics of the system of tables examined from the technical and medical angles.

CIRIA decompression tables UK - (1978 Construction Industry Research and Information Association). In this system, a heliox mixture with a nitrogen content at the quantifiable level is used during the plateau and during decompression, which requires special technical instrumentation of the diving system. Achieving such a high degree of purity of the breathing mixture requires the use of nitrogen-free gases (oxygen above 99.5 %) and its flushing out of the habitat before compression, which is very impractical and time-consuming. At the time, and even currently, this was not feasible under domestic conditions.

The tables used by the Italian company RANA and applied on the Petrobaltic platforms do not differ from the US Navy 1973 system from the point of view of the rate of depressurisation, but they do differ unfavourably in the conditions under which the decompressed divers are depressurised, with a lower pO_2 (0.33 ata), a higher pN_2 (1.32 ata) and the elimination of a two-hour break every 24 hours. These three deviations significantly increase the exposure of decompressed subjects in the 'Rana' system compared to the US Navy 1973 system, where the percentage of pressure sickness cases was 11% anyway, It should be noted that such a high invasiveness of decompression in the US Navy 1973 system prompted the NEDU (Navy Experimental Diving Unit) to make changes and convert it to the US Navy 1991 system. The considered exposure of divers to pressure sickness in the "Rana" system confirms the magnitude of critical oversaturation, according to Polish studies. A single one- to two-hour supersaturation of 0.4 - 0.5 ata in the final decompression phase causes symptoms of pressure sickness of the first type in a few to a dozen percent of divers. In contrast, the greater risks, exponent of which is a higher percentage of pressure sickness cases, cause similar supersaturations, but occurring repeatedly, or at an earlier stage of decompression. At the same time, uninterrupted low supersaturations over many hours, despite not yet causing symptoms, can put divers at risk of dysbaric osteonecrosis [4].

During operational saturation dives during decompression in 1995 and 1997, the exchange of the hyperbaric chamber atmosphere from heliox to air was used from a depth of 6.5m. This operation was not included in the official documents of the Italian RANA company [6]. The dive manager of the Italian team explained that this procedure was a physiological adaptation of the divers' lungs to breathe atmospheric air. Discussions with French specialists in 1999 indicated that such an operation avoids the "Chateau effect"; the difficulty of breathing low density gas, which can cause respiratory discomfort in divers [7].

US Navy 1991 system. There is no statistical data in the literature on this revised, latest US Navy saturation system. According to Prof. Doboszynski's assessment at the time, this method of decompressing divers with heliox, as opposed to the 'Rana' system, is safe, but offers very long decompression times. It is worth noting that the US Navy's 1991 saturation decompression system in question (after limiting the decompression rate in the zone to 60 m and eliminating the 6- and 2-hour stations provided for divers' sleep) was surprisingly similar to the national saturation decompression system validated in 1982 - 1989 in the habitat of the Naval Academy's ZSNiTPP. This suggests a convergence of views between the authors of the studies of the two centres, despite the earlier non-publication of preliminary results.[4] It is also worth noting the dates and thus the 'priority' of the concept.

Russian (Soviet Union) Navy system. The incidence of pressure sickness in this system was not published nor was the number of accidents reported in publicly available publications. The assessment shows that this method of decompression is also safer than the 'Rana' system, although the high initial decompression rate and the use of graduated pressure reduction (stations) raise reasonable doubts [4]. This system of tables was abandoned by the Soviet shipowner who ordered the GKW 200 diving systems from the Szczecin Shipyard in favour of a system of Polish decompression tables, which were tested during the delivery trials, unfortunately without the bell operation associated with the diver's work at depth as described earlier.

References

1. Skrzyński S., Pachut M., Olszański R.: „Helioksowe nurkowania saturowane w Morzu Bałtyckim”, V Konferencja Naukowo-szkoleniowa „Problemy medycyny oraz Nurkowanie – problemy techniczne” 1998.
2. Skrzyński S. „Wybrane problemy techniczno-organizacyjne wdrożenia nurkowań saturowanych”. Praca pk „ SATURN“ AMW 1998.
3. 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.
4. Doboszyński T., J.Kot, Z Sicko „System Nurkowań Saturowanych z użyciem Trimiksu w Strefie Głębokości 80 metrów dla Platformy Wiertniczej Petrobaltic” DSK – 95 Akademia Marynarki Wojennej 1995.
5. Skrzyński S., J.Pawlak ,S Wiśniewski Technologia Nurkowania Saturowanego w Kompleksie Nurkowym Af-2 LOTOS Petrobaltic S.A. Gdańsk 2011.
6. Normative Operative Requisiti di Sicurarzza RANA 1987. Rana” ”Working and Safety Regulation.
7. Skrzyński S., Dokumentacja pracy pk. NURSAT Nurkowania saturowane dla potrzeb Petrobaltic i LOTOS Petrobaltic z lat 1995-2000.

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