POLISH HYPERBARIC RESEARCH 4(77)2021
Journal of Polish Hyperbaric Medicine and Technology Society

# RESEARCH ON SATURATION DIVING IN POLAND AND ITS IMPLEMENTATION. PART I A. GENERAL CHARACTERISTICS OF SATURATION DIVING RESEARCH IN OUR POLAND. PIONEER TIMES; 1967- 1985

Stanisław Skrzyński

Department of Underwater Works Technology, Polish Naval Academy

## ABSTRACT

The article is the first in a series of articles on the research and implementation of saturation diving technology in our country which presents the specific Polish conditions and achievements against the background of economic and historical circumstances. In view of the fact that research and implementation has a history of more than half a century, selected key figures of this period are recalled, some of whom have disappeared in the fogs of history. In the specialized literature of the world, the Polish underwater habitats of Meduza are among top 6 countries that researched and implemented, this high technology of saturation diving. Regarded as the inspirer , pioneer and creator of the first saturation diving, he designed and developed the technique and decompression with the cooperation of a team of enthusiasts from clubs and professional divers, as well as engineering staff from the Tri-City enterprises. In the first part of the article the author characterizes the saturation dives in comparison with short dives with particular emphasis on decompression, which is the key to safe diving. The article also takes into account the technical conditions for the implementation of the first saturation dives. The author discusses the general methodology of validation and verification of the assumed decompression, referring to the Polish conditions. He describes how the medical, technical, and organizational problems of implementation of saturation diving were solved in the pioneering period against the background of world achievements. Furthermore, the author describes Polish habitat constructions of Meduza and Geonur types and their application to underwater work on the Polish shelf and coastal areas. Despite the great progress in the field of medicine and technology, as well as organization, the problems of saturation diving, despite the passage of time, remain relevant , as these are the most difficult dives from the point of view of organization, underwater physiology and safety technology.

**Keywords:** pioneering implementation of saturation diving, medical and technical problems of diver decompression, research validation of decompression tables, saturation diving, saturation diving parameters, underwater work, diving system, saturation diving, decompression of divers underwater habitat, decompression tables.

ARTICLE INFO

PolHypRes 2021 Vol. 77 Issue 4 pp. 53– 72

**ISSN:** 1734-7009 **eISSN:** 2084-0535

**DOI:** 10.2478/phr-2021-0021

Pages: 20, figures: 0, tables: 0

**page www of the periodical:** www.phr.net.pl

**Publisher**
Polish Hyperbaric Medicine and Technology Society

**Original article**

**Submission date: 13.05.2021 r.**
**Acceptance for print: 14.06.2021 r.**

## INTRODUCTORY INFORMATION ON SATURATION DIVING

Saturation diving is regarded as 'high-tech' for underwater commercial works. It is indispensable in rescuing people exposed to elevated pressure for long periods of time, and as a "last resort" in complicated decompression incidents. In commercial application, saturation diving is the most effective method of diving, but at the same time one that requires complex and complicated technical and organizational protection and high qualifications of the team performing it.

Poland prides itself on its history of research and implementation of these dives dating all the way back to 1967, not much shorter than other countries, including those at the forefront of marine technology worldwide. As a practical nation, just two years after the first successful commercial saturation dive, we began our own work on this, as we now know it, ground-breaking and extremely useful technology.

The problem of prolonged human exposure to increased pressure is not only related to the sea; during the same period, the subject was being addressed by physiologists in former Czechoslovakia. The main goal that science set for itself during this period was to ensure that humans could survive and work under increased pressure for the longest possible time, while ensuring their safety. This goal was also motivated by the many problems encountered on land, such as working in caissons. Another motivator was catastrophic events in which people stayed for long periods of time in water siphons under conditions of increased pressure. The problem of prolonged human work while under pressure also affects other, sometimes critical, fields. For instance, the construction of tunnels or bridges. And in the coming years, the technology of saturation diving will have to be used during the construction of wind turbine farms in the Baltic Sea, at depths at which the Polish pioneers of batynautics performed drills to take samples for bottom testing. These problems will resurface in our country after more than half a century, and will have to be solved formally, administratively and, inevitably, research-wise even if new foreign standards are adopted[1].

Extensive research into the adaptability of humans to work underwater, with the body's tissues fully saturated with inert gases, has been carried out in many countries. In maritime countries this took place mainly during the exploitation of shelf deposits, from the 1960s to the 1990s. The studies were preceded by research that began in the early 20th century related to work in caissons during the construction of bridges and underground railroad routes. The approaches to the issue of prolonged human habitation under pressure have varied so widely across different research centres that no single universally accepted standard for saturation diving can now be identified. A number of specialists consider as such the system of the US Navy. Relevant here is the fact that the systems developed abroad were proprietary and adapted to the technical solutions and level of hyperbaric technology of the country. In conclusion, the discrepancies in the different saturation diving systems used around the world are the result of both the diversity of views on the effects of phenomena occurring in the hyperbaric environment on the human body, and the amount of money allocated to research. [1]

An important role in the study and implementation of saturation diving continues to be played by the feedback of leading sciences. By these, we should understand underwater medicine and the departments of mechanics touching on hyperbaric technology, organization theory, ergonomics and also the so-called good diving practice. The technical solutions employed affect medical and organizational requirements. Also, engineering solutions have a major impact on the basic elements of the adopted saturation diving system. Proper technical preparation of a dive requires solving the following technical and organizational problems:

- the type of breathing mixtures used during the various phases of a saturation dive;
- parameters of the components of the atmosphere of hyperbaric facilities (microclimate);
- the method of raising the pressure, maintaining the pressure and parameters of the atmosphere; (compression and decompression of divers);
- determination of the safe depth zone of the divers' work in relation to the saturation plateau, *(The depth of saturation pressure, i.e., the stay of divers in hyperbaric chambers or underwater habitat);*
- determination of the time of divers' stay in conditions of increased pressure and their time in the water depths;
- ergonomics of the use of respiratory diving equipment and the method of thermal protection of the diver's body;
- hygiene of work and rest and nutrition of divers under conditions of increased pressure;
- microbiological and individual hygiene of divers;
- hygiene of divers before and after completing a saturation dive;
- the method of communication and observation of divers;
- the level of equipment reliability and technical redundancy thereof to secure a high level of safety of saturation diving.

The above-mentioned aspects and problems are reflected in regulations, standards and recommendations for the implementation of saturation diving. The requirements of these regulations for which the safety of divers is the primary goal are substantiated by scientific research. Said regulations are the result of accumulated experience over many years, which should not be forgotten.

The primary condition for the development of a safe saturation diving system, in addition to technical, medical, organizational and legal issues, is the availability of an experimental base. This base should meet all the necessary requirements to effectively secure the implementation of tasks for experimental divers and experimental pressure exposures on a laboratory scale. Equally important is the existence of the possibility of performing experimental saturation dives in marine conditions, which was impossible in our country for a certain period. The reason for this was the economic and political conditions and the lack of an adequate state programme in the coordination of activities in the field of underwater activities for the needs of defence and the national economy, while at the same time there was virtually no technical base for diving research in general [2].

In saturation diving, as in no other type of diving, the connection between the three leading fields is visible, i.e.: underwater medicine, technique in the broad spectrum of sciences that make up the technique, and organization, in which efficient and safe operation is crucial. Research on saturation diving has been, and continues to be, carried out along a multifold path. They require the participation of scholars and specialists from multiple sciences and domains of life, as well as scientists and specialized and engineering personnel combining, using and implementing selected knowledge resulting from research. In our country, the path of research and implementation of saturation diving has been very different from the accepted research sequence of leading countries. Saturation diving in Poland began without the participation of competent scientific centres, and resulted from the current needs of the maritime and mining industries and related geological research.

All major maritime nations have researched and worked on the development and implementation of saturation diving not only for commercial use, but also for purposes of defence. The development of the method was initiated in 1957 by a group of scientists from the U.S. Naval Diving Laboratory led by underwater medical specialists Cmdr. J. Bond and R. Workman. Their research on the theory of saturation diving, which they began, was implemented in the 1960s. The works were based on the thesis that inert gases dissolve in the body tissues of a diver staying at a given ambient pressure until they are fully saturated [3,4]. Once the diver's body is fully saturated with an inert gas, regardless of the amount of time the diver stays at a given pressure, no more gas will dissolve in his body. This results in a decompression time that is independent of the time spent under pressure after the time of complete tissue saturation (full saturation). In addition to this basic simplified thesis, other factors in saturation diving had to be studied, such as the effects of inert gases on the body, the psychophysical effects of the environment, the selection of divers, the hygiene of staying in a confined, limited space, the effects of the hyperbaric environment containing admixtures harmful to the body, bacterial and fungal flora, conditions and assessment of the diver's physical and mental fatigue, the diver's ability to perform, as well as the immediate and remote health effects on the body and treatment options for specific diving diseases including therapeutic recompression.

The main research challenge was from the technical angle to secure the long-term stay of the diver under pressure and the ability to work for a relatively long time in the water depths. The main problems here were to ensure the comfort of stay, adequate habitability - living space, ensuring hygiene of work and rest, ergonomics, reliable and credible measurements of diving parameters in all four phases of saturation diving (*compression , stay at the saturation plateau, work in the water depth and decompression*), transfer under pressure of people and equipment, provision of medical assistance and reliability of the system resistance to states and emergencies with which the problem of evacuation of a diver under pressure is associated. Each of the above-mentioned problems requires the cooperation of representatives of many technical specialties: designers, constructors, technologists and technicians of mechanical, chemical, metrological, electric, hydraulic and pneumatic drives, ergonomics, sanitary specialties, etc. [2]

The author, having reviewed the literature and drawing on his own research and professional experience, concludes that solving technical and organizational problems is described in the literature on a very limited scale. One could even say that it constitutes a secondary problem there. Medical and physiological problems dictated the technical requirements of diving parameters. Their suitability was evaluated only from a medical and, to a lesser extent, ergonomic point of view, through the prism of health and life safety of the diver participating in the experiment of a given diving technology.

Medical and technical research of saturation diving and its technical protection began with the construction of "underwater cabins" - habitats. In the course of the research, the depth - saturation level was increased and the transition was made from air as a breathing medium to nitrox, trimix and heliox mixtures in the depth zone of the sea shelf. The underwater habitat fulfilled its role in the first pioneering stage of saturation diving, but was impractical for use in the offshore industry, rescue and marine research. Moreover, it was very inconvenient from the point of view of handling and ensuring the comfort and safety of divers. A system of underwater habitats, such as Sealab-1, Sealab-2 i Sealab,3, TEKTITE-1, TEKTITE-2 (USA); Helgoland (FRG) and Chernomor (USRR) or our Polish solutions Meduza I and Meduza II, operated on the principles that compression, staying at depth of divers, and their decompression took place in its entirety in an underwater cabin. A special place in the use of underwater houses is occupied by the Aegir method, used by M. Runge (Hawaii). In this case, compression took place in an underwater cabin located at the pier. After filling the ballast tanks with water, the cabin was placed at the bottom where it remained during the course of the programme. At the end of the experiment, the ballast would be deflated, the apparatus would be resurfaced, and the divers would remain in it until the decompression phase was over. The Aegir was thus a unique combination of features of an underwater cabin, an onboard decompression chamber and a transport capsule.

The composition of the gas mixture in the submersible cabins varied. [5,4] For example, Sealab and Aegir used a helium-oxygen mixture, while TEKTITE, Helgoland and Chernomor used a nitrogen-oxygen mixture and air (at shallow depths) as did the Polish Meduza I and Meduza II [5,4,6].

To avoid inconvenience, the underwater cabin was brought to the surface where it served as a hyperbaric chamber and was maintained on the watercraft. This solution provided the mobility of using saturation diving technology without the need to transport the underwater habitat. In this technical solution, divers stayed at a pressure similar to that prevailing at the working depth, “lived” on the surface, and proceeded to the location of their tasks in a closed type diving bell with the same internal pressure as in the chamber. This was possible thanks to a technical solution allowing the transfer of divers under pressure (TUP), one of the most dangerous operations during a saturation dive. Such solutions arose almost parallel to underwater habitats in the late 1960s. At that time, the technique associated with the organization for the implementation of saturation dives began to be referred to as a “diving system.” The most technically complex element of the saturation diving system was and still is the closed-type diving bell, named so because, during the diving operation, the saturation plateau pressure prevails in it. The hatch of the bell opens and closes when the pressure between the environment and the interior of the bell is compensated, that is, in the depth of the diver's immersion-operation, or the pressure inside the chamber to which it is connected. The design of the closed-type bell drew on the experience of deep-sea diving and used additional technical solutions to feed divers' breathing apparatuses, supply warm water to diving suits and the bell for heating, maintain communications and lighting, carry out measurements, or maintain the parameters of the bell's atmosphere similar to a hyperbaric chamber at the saturation plateau on the surface. The apparatus providing these basic functions of the bell had to be integrated into its space.

The safety requirements for divers and the provision of assistance to them during probable medical and technical emergencies require additional equipment and components to be placed on or inside the bell for this purpose: stocks of gases, materials for life support and operation of gas, electrical and hydraulic systems, and emergency battery banks. This is aimed at achieving an assumed level of autonomy. The time of this autonomy has increased from 12 to 24 hours with development and increasing depth, and is currently 72 hours for bells operating at a depth of 300 meters. The bell's autonomy is necessary in case the power cable-hose bundle is detached from the surface or damaged. In an emergency situation of rupture of the power cable, the bell can surface autonomously after dropping the ballasts that provide it with negative buoyancy, and possibly cutting off the cable-hose bundle. In the literature, a closed diving bell is occasionally referred to as a "submersible hyperbaric chamber" (SDC) [7,8].

The method of saturation diving for commercial purposes was first employed by the oil company Westinghouse during works on the Smith Mountain breakwater. The company used a diving complex aboard the ship Cachalot, on which divers stayed under pressure in a chamber. They were transported to and from the pressurized chamber using a transport capsule, which was also kept under positive pressure. The divers spent 800 man-hours at the sea bottom over a 12-week period. The use of the Cachalot complex demonstrated that the saturation diving method can find wide application. Saturated divers stay under pressure in a decompression chamber located aboard a carrier ship and are transported to the work site also under pressure in a transport capsule or underwater decompression chamber. This system differed from other systems developed at the time using the underwater cabin principle: (Sealab-1, TEKTITE-1, TEKTITE-2 (USA); Helgoland (FRG) and Chernomor (USRR)). In these systems, compression was performed on the surface, followed by the divers being transported to an underwater cabin, where they remained until the completion of the programme. At the end of the experiment, the divers would return to the decompression chamber located on the surface.

Modern diving platforms located in the North Sea (such as Uncle John and the platform being built by Seaforth) are equipped with saturation diving systems, allowing diving 24 hours a day, 3 times each with three teams of three using two diving bells. The diving system is designed for 28 divers placed simultaneously under different saturation plateau pressures. The achievement of such a solution was made possible by high-intensity research conducted until the 1990s.

The result of this research has been the continuous development of emerging regulations for the construction of diving systems since the 1970s. The first regulations for the construction of diving systems for saturation diving were very detailed and reflected the results of research and experience of the particular country for which they were created. To date, virtually every maritime country operating a shelf has such regulations. International exchanges forced international recommendations (IMCA and IMO) to be created for cooperation. The first regulations were much more detailed, compared to those currently in use, especially the international ones which are at the level of general technical requirements [8].

In parallel with the regulations for the construction of diving systems occurs the formalization of regulations for deep and saturation diving. They include medical requirements, organizational requirements for diving and the necessary technique to perform the dive, as well as decompression procedures. These requirements are accompanied by recommendations for procedures to deal with the occurrence of diving diseases and procedures for therapeutic recompression. The aforementioned regulations reflect the medical and technical-organizational peculiarities of a country and protect its economic interests.

## GENERAL CHARACTERISTICS OF DECOMPRESSION IN SATURATION DIVING

Despite the passage of more than a century since the development of the first decompression guidelines, based on a scientific interpretation of the desaturation process (Paul Bert 1878), to this day no decompression method has been developed even for air dives that could be considered a standard method. Neither do we have a standard of tests to verify the correctness of decompression. Nor can we clearly indicate which divers will tolerate decompression loads better and which will tolerate them less well [1].

The primary problem in saturation diving and short-term diving, is to solve the issue of decompression of divers to the full extent, for all types of underwater work. This problem has been addressed in three problem groups, which constitute the entirety of diving. The most difficult research tasks face underwater medicine, starting with physiology, physiopathology, hygiene of the diver's work and rest, medical selection of experimental divers, and evaluation of their psychophysical condition. Related to this is the problem of assessing the effects of decompression on the health of the diver immediately after the dive, and the remote effects over a long period of time. Currently, the problems of remote effects are recognized research-wise, but rarely described in the literature.

The second leading problem is the evaluation (validation) of the decompression tables used. The extent to which research was conducted on this topic depended on the needs of industry and defence, the traditions of the country, the funds that were set aside for research, and the equipment and capabilities of the research base that scientists had at their disposal. For example, decompression research of one saturation dive at depths of 200-300m is an outlay of millions of dollars.

Decompression continues to be the most difficult phase of diving. Despite years of research and considerable investment in research work, the process is still not fully understood, and does not have a standard model, both in short-duration and saturation diving. In recent decades, the US Navy short-duration model has been adopted as a comparative model, but mainly in Anglo-Saxon countries. Decompression lacks an intermediate link between saturation diving and short duration diving. This lack is mainly due to economic grounds, and the difficulty of developing an efficiency-reasonable model for dives with stay times of more than 2 hours at depth, as well as limited technical protection for the diver's work at medium and low depths. For these dives, a base with a diving bell and active thermal protection of the diver's stay in the depths is necessary, which is not economically efficient.

In the 1970s and 1980s the concept of subsaturation dives existed in our country, i.e. for times below the body's full saturation time; leading tissue (i.e. 5-6 of its half saturation time).

During short-term diving, only so-called fast tissues (e.g., blood, lymph), with a relatively short half-saturation period, become fully saturated. In contrast, medium-speed and slow half-saturation tissues, saturate partially. The relations of these tissues for a selected time of stay at a given depth, i.e., pressure interaction, differ in the assumed level of their saturation, which implies the manifold nature of the decompression model. In saturation diving, the diver's body saturates all tissues in 100%, after a certain period of time of staying under a given pressure, known as the saturation plateau or saturation level.

The author of the article believes that in the Polish scientific community it has become accepted that decompression is managed and developed by doctors. Existing decompression models have mostly been and continue to be developed by physicists and mathematicians, but always with the participation of physicians and generally deal with the physics of the phenomenon of dissolution, permeation and release of gases in human tissues. Historically, the oldest and to date used in decompression modelling is the hypothesis of exponential saturation and dissolution of theoretical body tissues, which have no direct counterpart in reality [9,10].

An ideal decompression profile is one that, from a theoretical point of view, is tailored to create the largest possible gradient of inert gas elimination from the tissue without triggering bubble formation [11,9]. We know from the physics of the phenomenon that the rate of tissue saturation is greater the higher the pressure gradient between the pressure in the tissues and the external pressure, depending on the depth of the dive, the difference in the partial pressure of a given gas between the gas in the diver's lungs and the individual tissues. As the gas dissolves in the tissues, the magnitude of the gradient decreases due to a decrease in the difference in partial pressures between blood and tissues, resulting in a decrease in the amount of dissolved gas all the way to the end of the process. The amount of gas dissolved until full saturation will also depend on lung ventilation, and the amount of blood supplying the tissues per time unit (heart rate). The volumes of dissolved gas in the tissues will also depend on the type of inert gas, the mass of the tissue and its blood supply, or the position of the diver in the water depths. To verify decompression tables in the last decades of the 20th century, divers of height 175cm and weight 70kg were selected, and for saturation dives the criteria were even stricter. It was joked, for example, that a saturation diver should not knock down a bar at 165cm.

The time for full saturation of body tissues for saturation dives is assumed to be 30 to 36 hours for nitrogen as an inert gas and 26-28 hours for helium. In short-term dives, the so-called fast tissues become fully saturated much faster. (For instance, it is assumed that blood saturates within 28-30 minutes for a given ambient pressure) [6].

The saturation time of a given theoretical tissue is determined by a multiplication of the semi-saturation period, derived from the exponential, which is a sequence of components of a series of half-size numbers approaching zero. When practically applying the principles of decompression theory, 6 semi-saturation periods are taken as the time of full saturation. This is 98.5 99.5% of the full saturation time. For example, for a tissue with a semi-saturation period of 40 min, i.e. one of the leading tissues (i. e. considered in short-duration dives), the time to full saturation is about 240 min. For the theoretical tissues used in decompression saturation dives, a tissue with a semi-saturation period of 240 min reaches full saturation after being under pressure for more than a day. For theoretical tissues of 480 min, full saturation will occur after two days, and for tissue with a semi-saturation time of 720min after three days.

The decompression model is a representation of phenomena occurring in the body (in some approximation), which are verified by underwater physiology and have proven safe in practice. The saturation half-periods from 4 min to 480 min reproduce the processes of tissue saturation and dissolution to a sufficient approximation. In decompression tables based on the Haldane or neo-Haldane model, we operate with semi-saturation periods, e.g., RDP PADI's decompression model for short-duration dives considers 14 tissue types and adopts the following semi-saturation periods grouping them in multiples of minutes: 5', 10', 20', 30', 40', 60', 80', 100', 120', 160', 200', 240', 360', 480'. The U.S. Navy's tables for short-duration dives assume a smaller number of theoretical tissues. Their saturation half-times are 5, 10, 20, 40, 60, 80, 90, 100 and 120 minutes. The models used utilize a different grouping of time and values, and these are theoretical models for the mathematical description of very complex phenomena at the biological level. In short-duration diving, depending on the time spent at depth, several leading tissues are generally invoked, i.e., those that must be included in the process of dissolution so as not to exceed the permissible gradient of the difference of the so-called supersaturation, which is, to put it in a nutshell, the pressure difference between the tissues and the environment, which will not cause the formation of gas bubbles in the tissues causing decompression incidents and illnesses. As soon as the gradient of saturation pressure exceeds the permissible value, we define this as the supersaturation phase, and adjust the decompression time so as to eliminate this critical supersaturation. In other models based on theories of gas bubble growth or diffusion phenomena, we also operate pressures that we cannot exceed. The development of decompression procedures relies on avoiding critical supersaturation in tissues with different saturation half-times [9,10].

The first to introduce the method of calculating supersaturations was physician R D. Workman in the mid-

1960s. Based on decompression studies he conducted for the U.S. Navy Experimental Diving Unit (NEDU), he introduced the "M-value" (from the word maximum) for the determination of the limiting pressure gradient of the maximum inert gas that a given tissue can tolerate at a given ambient pressure without showing signs of decompression sickness. This method is also used in contemporary decompression tables. Calculating the value of supersaturation boils down to solving a simple linear equation M=ΔM*depth + M0.... in which the coefficients M are specific to a given theoretical tissue. M, or the maximum permissible tissue supersaturation for a given inert gas, is the sum of the zero saturation M0 and the product of the absolute pressure and the coefficient ΔM [11].

The decompression of saturation dives differs fundamentally from that used for short-duration dives in the dynamics of desaturation, i.e. the slow reduction of pressure over a long time interval. In the case of saturation diving, the development of the decompression method is, as a rule, based on one leading tissue with a relatively long saturation half-life, assuming that there will be no critical supersaturation in the remaining tissues, which is not certain in some models [11]. Most decompression models for saturation dives are based on continuous, slow depressurization with varying rates over given pressure ranges (e.g., 1.8mH2O/hr, 1.5mH2O/hr, 1.2mH2O/hr to 0.90 mH2O for US Navy tables). Decompression models for saturation dives use classical calculation methods, with this type of diving taking a theoretical tissue as the leading tissue with saturation half-times of 240min to 480min.

The first decompression models for saturation dives were adapted for diving using underwater habitats maintained at a given depth. The habits from the decompression models of short-duration diving, in which there is no possibility of smooth pressure changes, caused the first models to use fractional decompression, which was replaced by continuous decompression with time and experience gained. It has not been resolved which decompression is more effective, whether a step-by-step dosage of the saturation gradient or a smooth variation of this gradient [1]. The first experiments in the application of saturation diving using habitats required a surface base and a connection to that base, as well as a base power supply to protect the divers' vital processes. The decompression process of the aquanaut divers was associated with the ascent of the habitat, which required abrupt decompression. Such a solution for the implementation of decompression made it dependent on hydrometeorological conditions. Therefore, most of the experimental saturation dives took place in lakes or sheltered sea areas.

## EFFECT OF OXYGEN WINDOW ON DECOMPRESSION IN SATURATION DIVING

The oxygen window is also used in the decompression of saturation dives. Carbon dioxide, as a metabolic product, is removed from the body. It is 25 times more soluble in blood plasma than oxygen and, according to Henry's law, has a lower partial pressure. Such a distribution of partial pressures in the tissues and circulatory system provides a pressure difference between the pressure in the alveoli and the capillary system in the body's tissues. In the decompression of saturation dives, the level of oxygen partial pressure plays an important role. It is limited by the physiological effects of oxygen in terms of partial pressure and exposure time. During compression-decompression, active gases (oxygen, carbon dioxide, water vapor) are replaced by inert gases until the window stabilizes at the new ambient pressure level. By properly scheduling the decompression stops (taking into account the inherent undersaturation), the total tissue gas pressure can be maintained to be close to ambient pressure [12]. This approach to decompression is called "ascent without supersaturation." It is known to be very safe, especially for saturation dives, but it takes a very long time compared to ascent with limited supersaturation, which has been introduced in decompression algorithms for short-duration dives.

Staying on the saturation plateau and stays in the water depth and the bell require different breathing mixtures. In addition, the number of types of mixtures used varies depending on the depth and technology of saturation diving. For example, during compression, the so-called starting mixture or mixtures that are used in the compression process are employed. The composition of the mixtures must be selected in such a way as not to exceed a certain partial pressure of oxygen both in the process of staying on the plateau and while working at depth. The next group is emergency mixtures, used for treatment procedures and emergency conditions. In the selection of mixtures, we use the oxygen window. If the diver's work takes place at different depths than the saturation plateau depth, the composition of working mixtures uses the oxygen window to make the diver's return to the bell not require decompression, or to shorten it. In the existing and used decompression tables of saturation plateau dives, the oxygen partial pressure is taken to be 30kPa to 45kPa (0.3ata to 0.45ata). During decompression from 40kPa to 50kPa. In one case even 60kPa with the condition that decompression must not last longer than 56 h. In technically saturated dives it is possible to use isobaric decompression in which for 3-4 h on the saturation plateau the oxygen partial pressure is raised, for example, from 40kPa to 50kPa (0.4 to 0.5 ata). This allows the pressure to drop faster in the first phase of decompression [13].

## SATURATION DIVING PHASES

### DECOMPRESSION PHASE

In order to bring the divers' compression to the saturation plateau pressure within a certain time, the operation is performed slowly for two reasons. First, the compression phase is strictly programmed to maintain physiological requirements. This is carried out very slowly as compared to standard dives, from 10 to 15 m/hr, or even slower in the case of very deep dives (time defined by days due to the high pressure neurological syndrome, HPNS). The second factor lies in the technical capabilities of the diving system, and the need to ensure the comfort parameters of the chamber's atmosphere. The chamber must be technically prepared to homogenize the fed starting mixtures and control the composition of the atmosphere through forced gas circulation for continuous regeneration and to maintain the parameters with increasing pressure, so that after reaching the decompression plateau and the divers' adaptation time (from 12 to 24 hours), they can proceed to perform underwater tasks, i.e. transfer to the bell and descend.

### STAY AT THE PLATEAU

Staying at the plateau requires maintaining the parameters with a certain accuracy with the circulation of the regeneration stream, variable operating states of the chamber such as sleep of divers, preparation of divers for work, hygiene procedures, rest, etc. Life activities have a significant impact on the parameters of the chamber's atmosphere. For instance, physical exertion increases oxygen consumption and carbon dioxide release, humidity increases during bathing, as does the drying of wetsuits and warmers after returning from work in the water depths. The parameters of the state of the atmosphere are plateau pressure, carbonation, temperature, humidity, oxygen and CO2 partial pressure. Thermal comfort under helium atmospheric conditions dictates the accuracy of the measurement of the aforementioned parameters, but is in turn limited by the size of the regeneration flow such that, especially in helium atmospheres, divers do not experience thermal discomfort with a strong flow as well as related to the noise caused by the flow of gas.

### DECOMPRESSION

Decompression is generally a multi-day process. It can be implemented in a continuous or incremental (fractional) manner. In this dynamic process, the parameters, e.g. pO2,pCO2, must be kept constant, which, while securing the social needs of divers, complicates the process of its implementation. For example, the rate of depressurization during decompression varies from 1.8 to 0.6 m/hr, or in gradual decompression from 0.6 to 1.8 - 2m increments per hour. During decompression, we maintain a constant partial pressure of oxygen, which involves its proper dosage. Lowering the pressure changes the properties of the gases that affect measurement systems. For instance, the permissible content of carbon dioxide and oxygen when the total pressure is lowered increases, forcing the maintenance of reserves of multiple reference gases to control the readings of analyzers of these gases. After reaching 15m H2O, due to the fire hazard, the oxygen content is maintained at 20-22%, which extends the decompression process as the effect of the oxygen window decreases.

## VERIFICATION AND VALIDATION OF DECOMPRESSION TABLES OF SATURATION DIVES

In accordance with the provisions of the Declaration of Helsinki, after positive results of pressure effects studies on animals, the initiation of decompression studies involving humans requires the approval of a dedicated body assessing the risk to health and/or life of those participating in the experiment. Such approval for human research must be obtained for conducting decompression studies on divers. The Code of Medical Ethics, Law on the Profession of Physician and Dentist of December 5, 1996, specifies in Art. 41a the following: „A physician who conducts scientific research, in particular medical experiments, should comply with the standards and obligations of the Code of Medical Ethics and generally accepted principles of scientific research ethics." Medical research conducted with human subjects can be divided into two main types - intervention and observational studies. Intervention studies evaluate the effects of various factors on their participants. In the case of divers, this is decompression stress. Following an exposure to pressure, in turn, observation and data collection and analysis are carried out. Intervention and observational studies can be directed by both physicians and non-physician researchers. In Polish decompression studies, these have been led by physicians [2].

Each decompression table introduced into diving (not only commercial) obligatorily has to be verified and validated to ensure its accuracy, suitability and the most important indicator, i.e. safety. For each table, physiological and technical conditions for their implementation are defined. When creating decompression models, gas exchange kinetics and decompression quality criteria need to be defined. Gas exchange kinetics is a function that converts the dive profile into a cumulative decompression dose, which is the dissolved gas pressure in theoretical tissue [14]. Theory and experience show us that no decompression tables are 100% safe, and the safety of the tables is determined by specifying the probability of a decompression incident. Such an approach ignores a phenomenon that is very little studied, namely the distant effects of diving. With regard to saturation diving, from the beginning of its use, no method was known that would allow a comparative evaluation of the systems from the point of view of the exposure of divers to early or late symptoms of decompression sickness. Moreover, until the 1980s, the reliability of decompression systems was not statistically evaluated [13]. The gas pressure in the theoretical tissue is mainly a function of depth, time, partial pressure of oxygen, type of inert gas, water temperature and the diver's effort. Decompression verifications are based on two models, deterministic or statistical.

Decompression procedures of saturation dives are verified based on deterministic models. In this method, threshold criteria are defined for the tested decompression methods and procedures, which can never be exceeded. In deterministic models, the level of risk of exceeding the assumed decompression criteria is not specified. Deterministic decompression criteria usually consist of a set of maximum values of several critical variables. Any decompression program that keeps these values below the maximum value is acceptable. The final choice of decompression profile is made by the common application of the principle of minimizing decompression time.

Deterministic models are designed not allowing deviation from the proposed decompression profiles. They only allow exposures at various known in advance risk levels. The most commonly used function modeling the gas exchange model is the expotential correlation. Assumptions about gas exchange kinetics can be the same for deterministic as well as statistical models. The difference between the two approaches lies in the decompression criteria adopted. The accepted indicator of correct decompression is the absence of symptoms of decompression sickness. Symptoms of this condition never occur during descent-compression and stay under pressure, and only arise as a result of ascent, or a reduction in ambient pressure.

Statistical decompression models, as opposed to deterministic models, are based on calculating the probability of risk of DCS (decompression sickness). Statistical verification determines the level of risk that is acceptable for diver safety. In general, decompression criteria are primarily limited by variables that determine how depths and stop times at decompression stations should be distributed so as to limit the maximum value of the partial pressure of inert gas in the theoretical tissues during decompression.

Statistical decompression criteria are limited by an acceptable risk level for any decompression schedule. Any decompression schedule that does not exceed a certain risk level is acceptable. The use of statistical models is based on calculating the current probability of DCS occurrence. This probability is not only used to evaluate and validate the model, but also yields a quantitative measure of the quality of alignment between the mathematical theoretical model and experimental data in terms of predicting DCS risk [13].

Acceptance of a given decompression method is based on the number of decompression incidents or the number and size of gas bubbles present in the venous blood. The description of the phenomena accompanying decompression is a complex matter due to the lack of precise, unambiguous measurement methods that measure the processes occurring in the tissues of a living organism. Mathematical methods used to describe decompression tend to depict only approximate processes occurring during decompression. Such a description usually consists in fitting a relatively simple mathematical function to experimental data as accurately as possible. Such mathematical models should be considered only as a way of anticipating how to decompress safely, not as a reflection of physiological processes [15]. The commonly used way of evaluating decompression tables is based not on physiological criteria, but on pathophysiological ones, i.e. on symptoms of decompression sickness. As a consequence, the exponent of the tables' usefulness is essentially an arbitrarily accepted incidence of type I decompression sickness [1]. Meanwhile, any new diving technology requires the development of a decompression system appropriate for it, and thus the performance of certain studies with human subjects. Such studies definitely have the character of "health-risking experimental research." E.g., decompression classics Homer and Weathersby specify as confirmation that no more than 7% of decompression sickness cases will occur in the decompression system being evaluated. With a 95% confidence interval required, it is necessary to run 40 trials without incidents. With the same confidence interval, a successful run of 20 decompression attempts can only predict that the actual incidence of pressure sickness will be in the range of up to 17%. In contrast, obtaining confirmation that the incidence of cases in the decompression system under study will not exceed 5% requires hundreds of tests.

On this basis, the researchers of the subject expressed the view that it is impossible to validate the decompression tables of saturation dives with the required reliability without "considerable financial and human resources." The consequence of the specified correlations is the length of such a testing cycle, which is also confirmed by the cycle of our subsequent programs. The period of such testing should last 15 years with the application of large financial resources [3].

The presented methods of statistical evaluation of decompression (reducing the number of attempts) have become an undeniable achievement, but they offer only a partial solution to the problem of assessing divers' exposure to decompression sickness. First, they do not allow to express an opinion on the method of saturation decompression without simultaneous knowledge of the number of cases of decompression sickness and the number of dives (which data are usually unavailable). Secondly, with no cases of decompression sickness found in comparable decompression systems even with a significant number of attempts (10 - 20), they do not allow to determine which of them is more correct. It is clear from the above that the comparative assessment of diver safety in decompression systems is often beyond the reach of statistical methods. Also beyond their reach is the evaluation of newly designed systems [1].

Before embarking on a research programme, it is incumbent on the implementers to answer the question of whether the moral and legal responsibility associated with implementing an experimental research programme on a new diving technology and decompression method will be balanced by the results achieved. When undertaking the research, we were faced with a dilemma in Poland, as in other countries, whether to embark on our own research with a difficult-to-predict outcome, or to choose the best of the saturation decompression methods already in use. Polish decompression research in its pioneering phase was based on data acquired from the West, with incomplete information due to lack of access to research results (the so-called "Iron Curtain").

## GENERAL TECHNICAL AND ORGANIZATIONAL RESEARCH PROBLEMS OF IMPLEMENTING SATURATION DIVING

In order for divers to be able to safely penetrate and explore the bottoms of the seas and oceans, they use increasingly sophisticated equipment and complex systems to support their stay in the depths. Among the group of main equipment supporting divers are sets of facilities formerly known as complexes, or, in modern times, diving systems. Their main components are decompression chambers, also called hyperbaric chambers.

The diving system is the place where divers rest and recuperate. Thus, appropriate microclimate and thermal comfort conditions must be created for them, similar to those in normobaric conditions. At the same time, the spaces of the diving system must provide room for putting on diving equipment, transporting the diver to work, his return to the saturation plateau and performing post-dive activities such as checking and maintaining the equipment and preparing the equipment for the subsequent dive.

The microclimate of the hyperbaric environment consists of:

- pressure prevailing in the hyperbaric chamber,
- humidity prevailing in the hyperbaric chamber,
- temperature prevailing in the hyperbaric chamber,
- flow rate of the respiratory agent,
- type of breathing medium used, determining the partial pressure of oxygen and its content in the lower and upper limits,
- pollutants – especially CO2 (formed by the diver's exhaling as a product of metabolism. This is an important parameter that speaks to the need for ventilation and regeneration of the atmosphere).

As a result of gas exchange in the lungs, divers exhale carbon dioxide into the chamber. Given the limited volume of the habitat, this contamination accumulates,

- causing health risks for divers.
- The primary purpose of regeneration, therefore, is to purify the breathing atmosphere and maintain microclimate conditions by replacing certain volumes of used gas with fresh gas.

The primary functions of diving system equipment include:

- removal of physiologically generated pollutants, including carbon dioxide and other products of metabolism,
- removal of biological hazards, caused by bacterial and fungal flora,
- removal of pollutants generated during the operation of the complex,
- supplementing the oxygen consumed by divers by feeding and spreading it in the habitat,
- maintaining a homogeneous composition of the breathing atmosphere in the entire complex,
- use of breathing equipment with minimal consumption of breathing mixtures,
- selection of breathing mixtures with respect to the saturation plateau, the diver's work in the depth zone of the underwater task acceptable for physiological reasons and the breathing resistance of the breathing equipment,
- maintaining and regulating the divers' thermal comfort and the microclimate of the hyperbaric space of the bell and chamber,
- using active heating of divers' suits, allowing the diver to stay in the depths for several hours. [16,17].

The research and development along with the construction of a safe and utilitarian diving system for saturation diving has required involvement of a wide range of specialties. This entails the participation of scientists, engineers, technicians, organizer-managers, theoreticians and practitioners from such sciences as medicine (including underwater medicine), mechanics, materials engineering, ergonomics, specialists in safety systems, communications, hydroacoustics, metrology, psychology, etc.

The Polish story seems to contradict the above conditions. In the Polish version of the research, the volitional element was important, in which the most vital and basic element is the people fascinated by bathynautics. Their persistence and ability to overcome difficulties and realize their vision were and are at the highest level with the simultaneous passivity or sometimes even total lack of involvement on the part of academics dealing with the issue. The problem was taken up largely by people engaged in amateur diving, joined by a handful of specialists and professional divers. These were enthusiasts, passionate divers, working underwater with admirable courage. These individuals were the driving force behind the team solving the problem of new-type diving. This team was joined by pragmatic people, eager for success not only in financial terms, but also sharing a desire for adventure, and ordinary people who were drawn to participate in the programme aimed at introducing progress. It was under such conditions that the first saturation dives took place in our country, admired around the world, yet received with surprise due to the adopted plateau parameters of saturation at too great depths using air. Even more surprising was the fact that prior to the experiment under natural conditions, no laboratory tests or under natural conditions were performed (in chambers at plateau depths of 12m gradually increasing time and depths) as it was the case in countries at the forefront of this field [5,4,7].

## REFERENCES

1. Doboszyński T. „Problematyka badań doświadczalnych z udziałem ludzi a wdrażana technologia nurkowania" IV Sympozjum -- Nurkowanie-Problematyka Techniczna. Akademia Marynarki Wojennej.Gdynia 1994.
2. Dokumentacja techniczne i organizacyjna CPBR - 9.5 "Techniczne, medyczne i prawne problemy długotrwałego przebywania człowieka pod wodą,"Systemów podtrzymania życia kompleksu nurkowego GWK- 200". Akademia Marynarki Wojennej. Stocznia Szczecińska im. A.Warskiego 1990r
3. R.D Vann "Comprhensive strategy for saturation decompression with nitrogen-oxygen" Workshop on Decompression from NITRIX Saturation Diving January 8-9 1985 Institute for Environmental Medicine University of Pennsylvania
4. Miller J.W ,Koblick I.G Living and Working in the sea VanNostrand Reinghold Company ISBN 0-442-26084-9 1984,
5. Miller J NOOA Diving Manual Diving of Science andTechnology. 2-end editionUS GovermentPrinting OfficeWashington DC 1979.
6. Zespół autorów p.k.S.A.Guliar ,,Organizm czełowieka i podwodnaja sreda`` Zdorowie Kijew 1977
7. US Navy Diving Manual, 1991
8. Przepisy Towarzystw Klasyfikacyjnych DNV,ABS , Lloyd RS MRS z powstałych w II połowie XX wieku.
9. Bennet P.B and.Elliot B.H,,The Physiology and Medicine of Diving`` 2, 3 edition London, Philadelfhia, Toronto, Tokyo 1993
10. Vann R D „Comprehensive Strategy For Saturation Decompression with Nitrogen-Oxygen Duke Univ Medical Center Durham 1984 Feb
11. Wienke B.R. ,,Basic Decompression Theory and Application". Best Publishing Company, Flagstaff. USA 1991.
12. Lambertsen N C.J.: Basic Requirements for Improving Diving Dept. and Decompression Tolerance, 21 Proceedings from Conferense "Potential Adwances in Deep Diving". Baltimore, 1967.
13. 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.
14. Kenny J.E.: Business of diving. Gulf Publishing: Houston 1972 .
15. Dębski A. „Niektóre problemy batynautyczne w służbie potrzeb gospodarczych" Biuletyn Informacyjny 1-2 1975 Polskie Towarzystwo Przyjaciół Nauk o Ziemi
16. HAUX G.: „Underwater enginiering. Balliere Tindell ISBN 0-7020-0749-8. London 1982.
17. Wymagania dotyczące parametrów technicznych kompleksu nurkowego" Centralny Program badawczo-rozwojowy 95 cel 31.Wyższa Szkoła Marynarki Wojennej. Gdynia 1987.

---

*[1] Note For the purposes of this article "a long-term human stay under pressure shall be considered to be a time greater than the permissible diving depth stay times stipulated in the decompression tables for short-term diving, including the tables for emergency cases in which full saturation with inert gas of all tissues of the human body has occurred for a given ambient pressure. Contrary to the interpretation of the Law On Underwater Works of October 17, 2003, long-term underwater works are - "underwater works, the duration of which exceeds 8 hours, consisting of a single continuous diver remaining under the influence of elevated pressure while working below the water surface and while on the surface in a hyperbaric chamber." Such a term includes short duration dives using air and breathing mixtures.*

**Stanisław Skrzyński**
Akademia Marynarki Wojennej
im. Bohaterów Westerplatte 81 – 103 Gdynia 3
ul. Śmidowicza 69
tel.: +58 626 27 46,
e-mail: skrzynski@interecho.com