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STUDIES ON SATURATION DIVING IN POLAND AND PRACTICAL APPLICATION OF THEIR FINDINGS. PART 2 C. DEVELOPING A POLISH SYSTEM OF SATURATION DIVING IN THE 1980S AND 1990S

Stanisław Skrzyński[1)], Grzegorz Grzeczka[2)]

[1)] Department of Underwater Works Technology, Polish Naval Academy in Gdynia, Poland
[2)] Institute of Ship Electrical Engineering and Automation, Polish Naval Academy in Gdynia, Poland

ABSTRACT

This article is another in a series of articles on the research and the deployment of saturation diving technology in our country. This part discusses Polish specificities and achievements against the background of economic and historical context. It describes the creation of the base for saturation diving in the times of economic hardship in our country. Over this period, the shipbuilding industry was driving saturation diving research as a basis for the construction of diving systems to be exported to secure the extraction of the resources from the sea shelf. This paper describes the efforts of the animators and protagonists of underwater research in our country, whose work is continued to this day. In its second part the author shows how the Polish system of saturation diving was created. The article also considers the technical and organisational conditions in which the first saturation dives took place and the history of the development of the Polish decompression method for saturation diving. A key role in this difficult task was played by the creation of a base for this industry and research potential, assisted by the relevant state agencies, dedicated for the defence sector. A multiannual National Research and Development Plan (Polish abbr. CPBR) was set up with objectives 9.2 and 9.5 focused on medical and technical research resulting in the development of a diving system with its organisational framework, medical safety solutions, and reliable technology. The outcomes of this programme are still being implemented today. Despite advances in the medical and technical fields as well as organisation, the problems of saturation diving are still pertinent because, regardless of its complexity and high cost, this is the most efficient diving format that allows for very deep diving operations, currently up to 400-500m.

Keywords: diving research base, implementation of saturation diving, medical and technical problems of divers' decompression, saturation diving, diver life support systems, diving system, saturation diving, decompression tables, diving organisation, nitrox, trimix.

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SELECTED TECHNICAL AND ORGANISATIONAL RESEARCH PROBLEMS OF THE POLISH SATURATION DIVING SYSTEM

Technical research and organisational activities were directed towards the production of diving equipment and devices that were to be used as the equipment in the DGKN-120, GWK-4200, LSH-200 units, and their testing under operating conditions. The construction of the life support equipment, the heart of any diving unit, required carrying out a full 'development-implementation' research cycle. Technically complex medical requirements had to be taken into account, and full control of the chamber and diving bell atmospheric parameters had to be secured, both during normal operation of the diving complex and in emergency situations.

To have full control of the chamber atmosphere, one needs to be able to make a quantitative and qualitative assessment of the following eight factors [1]:

- overall pressure,
- oxygen partial pressure p_{O2},
- the partial pressure of carbon dioxide p_{CO2},
- temperature and humidity t, φ,
- toxic substances Z, p_x,
- fire danger,
- bacterial flora,
- noise.

As part of this programme, after a series of 15 experiments carried out in 1990, a depth of 100 m on a helium-nitrogen-oxygen mixture (trimix) was reached. The longest saturation exposure lasted over eight days. All exposures until 1994 were carried out to validate decompression tables. The duration of the saturation exposure ranged from 72 to 196 hours.

At the same time, the Department prepared teams of divers and technical personnel from the shipyard for the approval tests, and carried out research and tests of equipment for the GWK-200 diving unit. 24 tester divers took part in the exposures, giving an exposure of more than 100 people [2].

Each diving system can be characterised by the technical conditions that ensure diving safety, which are set out in the country's classification regulations. The structure of the safety system was based on the high standards of the Norwegian classification society DNV according to the requirements of the Soviet shipowner. In the technical and organisational tasks, the most important elements of the designed diving system included [3]:

- The ability to prepare a dive and work according to the requirements of diving technology and underwater work.
- Control of divers' compression.
- Control and supervision of the diver's stay at the saturation plateau and working depth.
- Decompression as required by the developed decompression tables.
- Carrying out typical emergency and therapeutic recompression procedures.
- Resilience of technology and organisation to emergency conditions and situations.
- Maintaining the assumed diving parameters with the specified accuracy.

To secure the operating performance of the diving system, intertwined technical, medical and organisational requirements were identified. The leading one among them was the organisation of research and experiments, which remained under the sole responsibility and supervision of the Department of Diving Equipment and Technology of Underwater Works (Polish abbr. ZSNiTPP): [4]

- specialist skills and health status required of the divers,
- the required level of technology literacy,
- the correct setting up of the diving base,
- acceptable hydrometeorological conditions at the site,
- the appropriate level of training and skills of the operating personnel,
- proper organisation, servicing, and sticking to the diving hygiene rules.

The following table shows the conditions that had to be met by the technology and installations of the DGKN-120 diving complex.

During decompression, when the pressure was reduced in a continuous way in accordance with the attached plan, the rate of depressurisation, the required pO_2 and the prescribed microclimate conditions were strictly adhered to. The decompression depressurisation of the chamber is related to the rationing of oxygen due to its loss caused by the continuous controlled release of the mixture and its consumption by the divers.

Tab. 1

Microclimate parameters recommended for saturation exposures in the chamber [1].

Depth [m]	Temperature ºC	Humidity % of relative humidity	Mixture movement cm/sec.
100	29 – 30	40 – 60	10 – 15
90	29 – 30	40 – 60	10 – 15
80	28 – 29	40 – 60	10 – 15
70	28 – 29	40 – 60	10 – 15
60	28 – 29	40 – 60	10 – 15
50	28 – 29	40 – 60	10 – 15
40	28 – 29	40 – 60	10 – 15
30	27 – 28	40 – 60	10 – 15
20	27 – 28	40 – 60	10 – 15
10	27 – 28	40 – 60	10 – 15
0	27 – 28	40 – 60	10 – 15

Figure 1 assumes ventilation for the three states of the chamber during decompression, i.e.; work, sleep and stay for q_{CO2} exhaled by the diver corresponds to q_{CO2} of 0.3 dm^3/min, 0.5 dm^3/min, 0.8 dm^3/min respectively for CO_2 content in the regenerated mixture A_{wk} = 0.0001 dm^3/m^3.

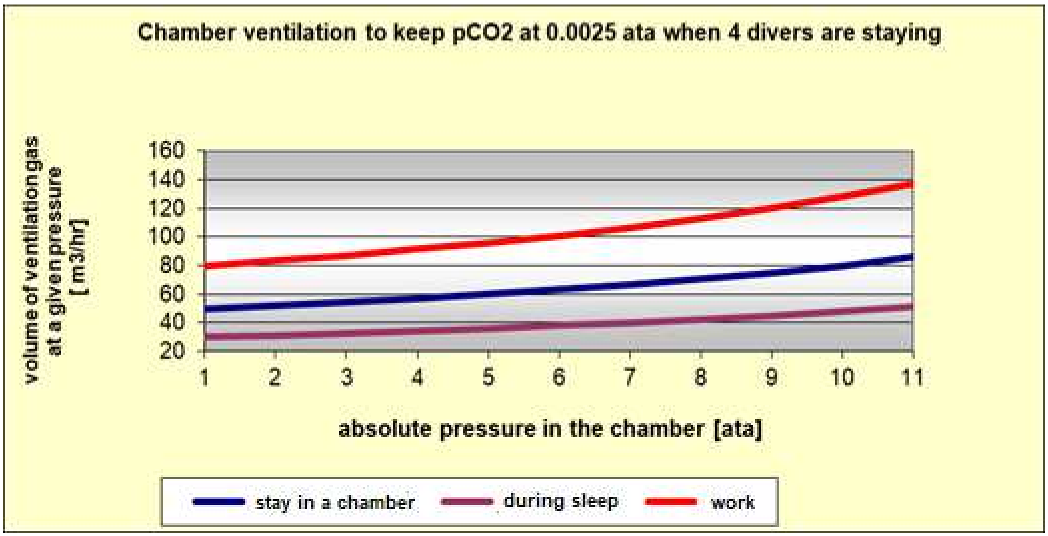

Fig. 1 Chamber ventilation for three principal states of the chamber for acceptable pCO2 - the volume of ventilating gas depressurized to the pressure in the chamber.

The use of a closed circuit for the complete purification of the chamber atmosphere by continuous ventilation is a necessary condition for safety [5]. The intensity of ventilation, the quality of the purification of the atmosphere, and the maintenance of temperature and humidity at adequate levels are controlled by measuring the composition and parameters of the atmosphere.

During decompression, it is even more difficult to maintain atmospheric parameters as the composition of the chamber atmosphere changes with decreasing pressure. For basic gases such as oxygen and carbon dioxide, the composition of the atmosphere should be monitored continuously, while for inert gases and harmful admixtures, it should be monitored periodically [6]. Temperature and humidity should also be continuously monitored. It should be emphasised once again that during a saturation dive, when a diver is subjected to pressure for a period of several days to several weeks, not only must CO_2 be removed and O_2 replenished, but thermal equilibrium and humidity must also be maintained while metabolic gases must be removed.

CO_2 removal is carried out using sorbents in the form of calcium and sodium hydroxides and potassium hydroxides [85].The removal of other harmful admixtures, with the exception of catalytic removal of carbon monoxide and nitrogen oxides, is based on the use of passive substances such as activated carbon and molecular sieves [5].

Humidity and temperature are maintained by an adequate ventilation system in the chamber, where excess humidity is condensed, and to maintain the correct temperature in the chamber the gases are heated at the inlet. To maintain the proper temperature of the chamber and the diving bell, both are additionally equipped with internal heaters [2]. The problem of maintaining the required humidity occurs not only during decompression. An increase in condensation inside the chamber, in addition to making divers feel uncomfortable, multiplies the susceptibility of the skin to infections [7,8]. On the other hand, the increased humidity caused, for example, by divers' bathing is beneficial for fire protection

especially as the oxygen content in the chamber increases during decompression. No such adverse events were encountered during the decompression tests. According to the methodology, the levels of toxic substances and the level of fire hazard are determined at the stage of system approval testing. To maintain a low level of hazard during the dive, specific hygienic procedures are followed in the chamber and full control of materials sluiced into the chamber is maintained. An increase in the oxygen content of the chamber's atmosphere while maintaining its constant partial pressure during continuous decompression to a depth of 15 m, corresponds to an oxygen content of 22 %, which poses a fire hazard. The rates of depressurisation are therefore prolonged, as the assumed oxygen partial pressure decreases with depressurisation. Oxygen is fed into the chamber in small portions, to a point in the chamber where rapid mixing with the atmosphere is ensured. This usually takes place near the suction port of the life support system [9].

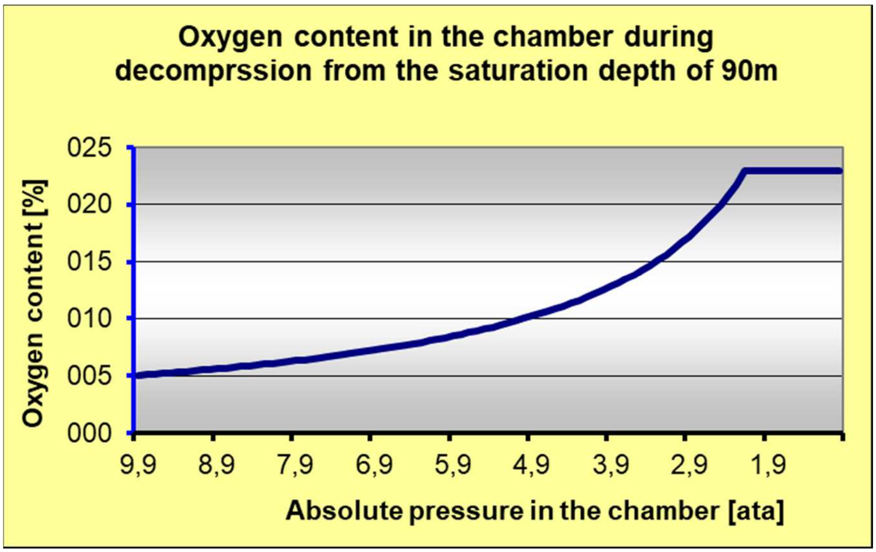

Fig. 2 Changes in oxygen content in the chamber in the entire decompression stage at saturation plateau 90 m.

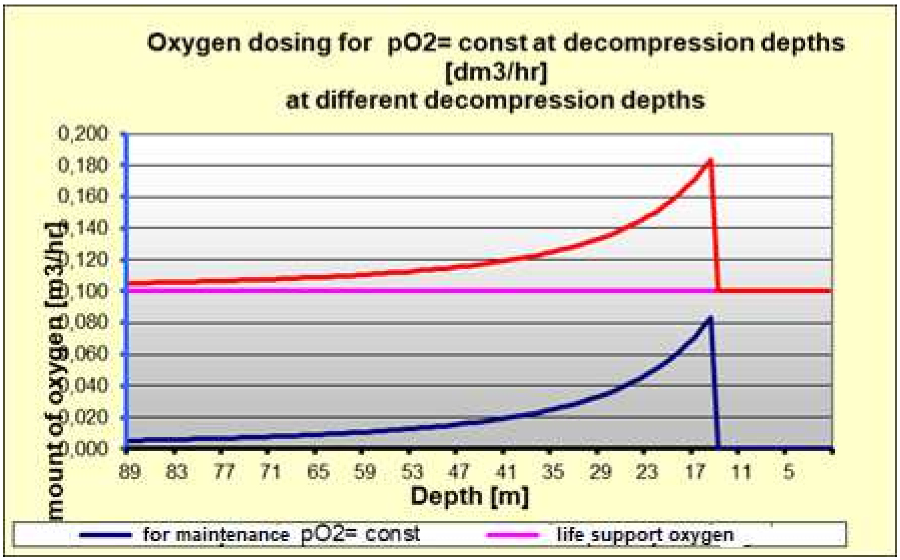

Fig. 3 Oxygen dosing during decompression of saturation diving.

During testing, the level of each of the above-mentioned factors must be measured and assessed quantitatively and qualitatively. For this purpose, it is necessary to design and build a suitable measurement system, and to develop a methodology for conducting measurements during saturation diving. Each of the above-mentioned factors has its own measurement specificities, which are influenced by the decompression procedure. It should be assumed that the measuring methods and instruments should secure the performance of all types of decompression. This condition requires the selection of measuring instruments of sufficient accuracy under conditions of varying pressure and other parameters.

The above conditions have coincided with the development of digital metrology and measurement systems supporting the development of modern technologies based not only on energy flow, but also on information flow. In a way, the measurement system integrates the individual narrowly specialised areas of saturation diving. The replacement of classical measuring circuits was and still is primarily due to the possibility of using monolithic systems, where fewer components are required, as well as digital calibration and automatic correction, i.e., self-testing and self-diagnosis.

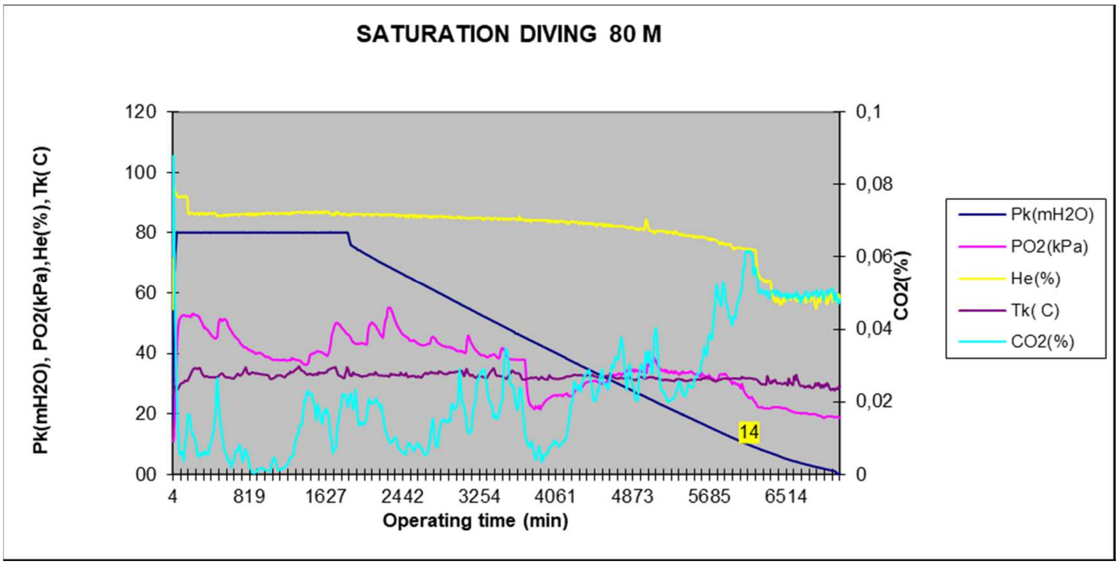

Fig. 4 The course of saturation exposure from saturation plateau 900 kPa [10].

The speed of the instrument's response to a change in a given parameter results from the characteristics of the decompression process [5]. This is especially true for pressure measurements: p_{ck}, p_{O2}, p_{CO2}, as well as temperature and humidity

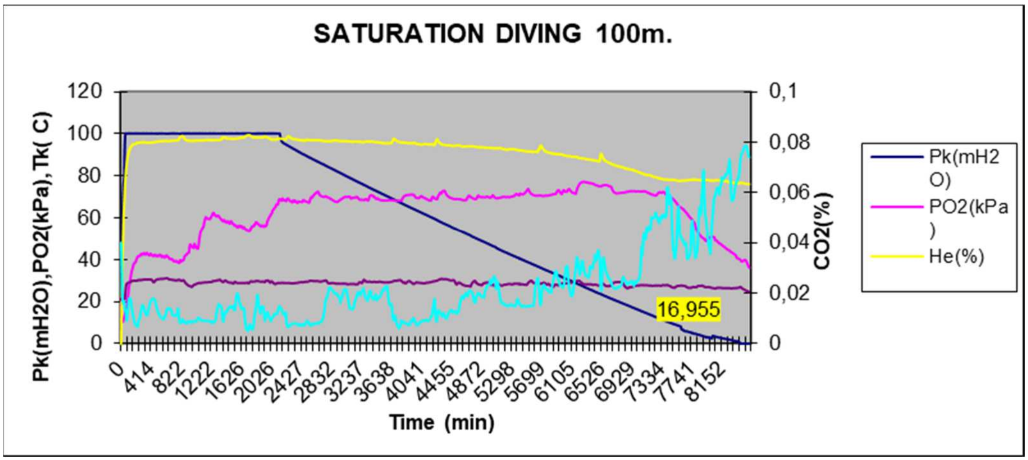

Fig. 5 The course of saturation exposure for saturation plateau 1100 kPa [22].

A very rare problem reported in the literature was the measurement and removal of gases (harmful admixtures) that were the product of metabolic processes, such as hydrogen sulphide, ammonia, methane, carbon monoxide, acetone and others. Studies have shown that they were removed in life support system filters containing activated carbon, molecular sieves and hopcalites [10]. Bacteria were and are also retained on strongly alkaline dioxide sorbents. In an ecologically isolated space such as a chamber, sources of noxious gases and dust can include paint, shielding, divers' clothing, sanitary items, etc.

Tab. 2

Example of the start of decompression stage from saturation plateau of 100m of the Polish system of tables [6].

Lp.	Depth range meters	Stop time minutes	Total time
1	100.0 – 99.0	5	0 HR. 5 MIN.
2	99.0 – 98.0	6	0 HR. 11 MIN.
3	98.0 – 97.0	9	0 HR. 20 MIN.
4	97.0 – 96.0	12	0 HR. 32 MIN.
5	96.0 – 95.5	17	0 HR. 49 MIN.
6	95.5 – 95.0	25	1 HR. 14 MIN.
7	95.0 – 94.5	25	1 HR. 39 MIN.
8	94.5 – 94.0	25	2 HR. 4 MIN.

A method of decompressing saturation divers at pressures of up to 1100 kPa and above, especially for hyperbaric complexes consists in saturating with a breathing mixture containing oxygen and helium and maintaining a constant partial pressure of oxygen within preset limits. Decompression of saturation divers is carried out from all depths continuously, without stopping at pressure drop stations, using a breathing mixture similar to plateau (trimix), with the rate of ascent depending on the partial pressure of oxygen and the depth of descent, where the partial pressure of oxygen for specific environmental conditions is constant to a depth of not less than 15 metres of water column and then decreases steadily down to the pressure of 21 kPa.

Tab. 3

Example of the final decompression stage from saturation plateau of 100 m of the Polish system of tables [6].

Lp.	DEPTH RANGE METRES	STOP TIME MINUTES	TOTAL TIME
187	5.0 – 4.5	53	96 HR. 37 MIN.
188	4.5 – 4.0	55	97 HR. 32 MIN.
189	4.0 – 3.5	57	98 HR. 29 MIN.
190	3.5 – 3.0	60	99 HR. 29 MIN.
191	3.0 – 2.5	62	100 HR. 31 MIN.
192	2.5 – 2.0	65	101 HR. 36 MIN.
193	2.0 – 1.5	68	102 HR. 44 MIN.
194	1.5 – 1.0	72	103 HR. 56 MIN.
195	1.0 – 0.5	20	104 HR. 16 MIN.

A half-metre pressure drop occurs in between 5 and 72 minutes. The very low pressures required a special technical approach, related to the operation of selected measuring and sanitary equipment whose operating principle is founded on the difference between the pressure in the chamber and in the environment.

A third source of contamination can be chemicals and products accidentally introduced into the chamber. In this case, the filtration system incorporated in the life support systems fulfilled its purpose. This was evidenced by periodic measurements carried out on harmful admixtures with explosimeters and indicator tubes at atmospheric pressure on samples taken. The baseline conditions for the design of life-support systems list about 30 substances whose concentrations should not be exceeded for prolonged stays in the chamber. During one exposure, the physician who examined hazardous admixture used polyethylene tubing to collect gas samples from the chamber. These were not properly cleaned of TRI skimming agent residues. Consequently, Miriam detected phosgene with the toxic gas instrument.

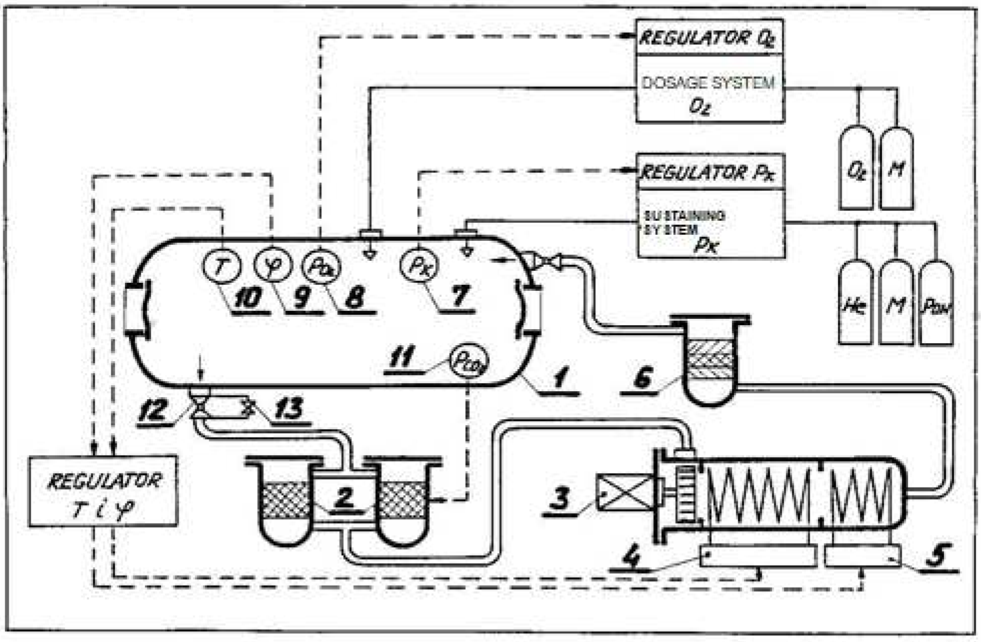

Fig. 6 Functional diagram of the operation of the basic external life support system with automatic parameter control used in GWK -200 and LSH -200 [11]. *Symbols.- hyperbaric chamber, 2 - filter - sorbent, CO_2, 3 - fan 4 - refrigeration system, 5 - heater system, 6 - activated carbon hopcalite filter (for absorber of harmful admixtures), 7, 8, 9, 10, 11 - sensors for measurement of composition parameters.*

Ventilation is the parameter that quantitatively characterises the regenerative capacity of the chamber atmosphere. The correct adjustment of the microclimate and the hygiene of the living conditions depend on the correct operation of the basic life support systems, in which the regeneration and purification of the chamber atmosphere from harmful gases and admixtures is carried out. The gas stream pumped into the chamber by means of a suitable fan, in addition to replacing the purified atmosphere, must also ensure its uniformity - homogeneity within the chamber space. This is important for two reasons. Firstly to prevent the formation of oxygen pockets when dispensing gases, which can result in a fire in the chamber. The second reason is to select a suitable sampling location for atmospheric composition measurements so that the results are not affected by the amount of ventilation, interference by diver activity and the distribution of the purge gas flow [5,12]. The flow distribution and circulation of the chamber's atmosphere were checked using a thermal imaging camera, which was only possible using a simulator and under atmospheric pressure conditions.

The study showed that, in practice, the intensity of ventilation for a fixed number of tester divers in the chamber is mainly determined by two parameters: p_{CO2} and φ. Measurements of toxic admixtures during saturation exposure of the diving unit were performed periodically, initially every 12 h and, after positive initial results, once a day [3]. The level of bacterial flora in the accommodation chamber was checked during the study.

When a diver is cold, he consumes more oxygen and exhales more carbon dioxide. The atmosphere can be warmed in two ways: by increasing ventilation, which will result in a concomitant decrease in carbon dioxide, or heating the gas stream, which in turn will increase the absorption capacity of the CO_2 filter and also decrease the amount of CO_2 exhaled by divers.

The relationship between oxygen consumption and humidity levels, temperature and carbon dioxide exhaled is taken into account in the design of life support systems [5]. In our study, two life support system layouts were developed and investigated. The first, working on the principle of regeneration of carbon dioxide sorbents, was based on molecular sieves. This system operating principle was founded on regenerating the absorbent capacity of the sorbents. Once the sorbent was saturated with carbon dioxide in the filter, a second carbon dioxide filter switched on in parallel took over the operation. The filter with saturated sorbent was regenerated with a hot air stream at 300°C. After a regeneration period of 2 hours, the filter was ready to operate again. This is why the system was referred to as 'hot.' At the time, this was a pioneering solution, proposed by Medard Przylipiak. The Soviet shipowner rejected it because, as he claimed, 'there were no similar examples of such solutions in the foreign literature.'

The basic external life-support system with automatic parameter control, was a system with disposable carbon dioxide sorbents that chemically bound the gas and, after overworking, the sorbent was removed and the absorber filled with fresh one. This solution was approved by the Soviet shipowner. We called this system a standard regeneration system, as all carbon dioxide absorbers in diving technology at that time worked on the basis of replaceable alkaline sorbents (composed of sodium hydroxide, potassium hydroxide or a combination of hydroxides of these alkalis).

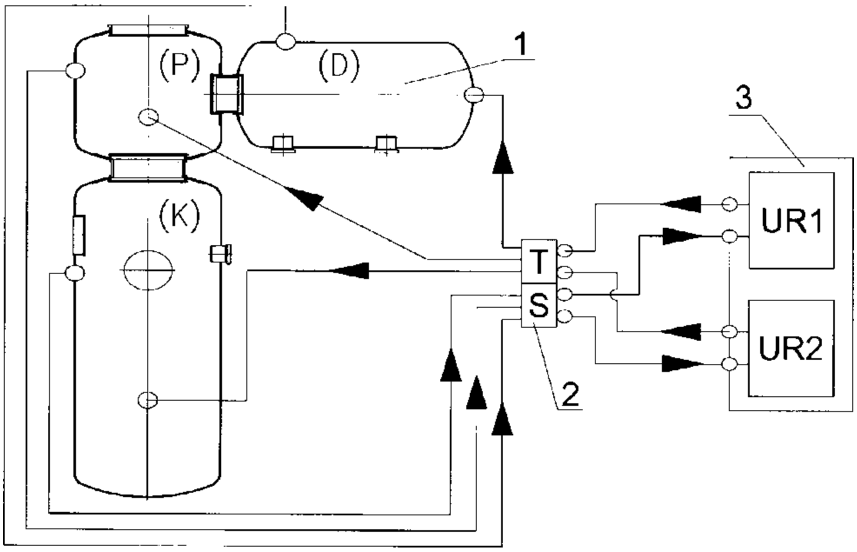

Fig. 7 Schematic breathing atmosphere circuit used in the DGKN-120 diving complex, forced out by a set of basic regeneration systems [13].
Symbols: 1 - decompression chambers of the diving complex (K), (P), (D), 2 - gas (breathing atmosphere) switchgear; 3 - transport container with regeneration system assembly, S - outlet (suction) manifold of the switchgear, T - inlet manifold (pressure UR chamber atmosphere regeneration system).

The life support system worked in conjunction with an automatic oxygen dosing system, operating on the principle of maintaining a constant adjustable partial pressure of this gas, which in turn secured its maintenance during plateau and decompression.

The development of decompression tables takes into account the accuracy with which the parameters will be measured. The requirements are defined on the basis of applicable regulations. [14,6]. Prior to diver testing, the DGKN-120 complex was functionally tested using a contamination and humidity simulator, and the dynamics of temperature change and maintenance. The noise levels produced by the atmospheric regeneration and primary life support systems of the DGKN-120 and GWK-200 diving units were also investigated. The noise levels were tested under conditions of maximum allowable ventilation, which also involved maintaining an allowable flow of breathing gas through the chamber.

Fire in the chamber is considered to be the greatest hazard, caused by handling and operation, which increases as the percentage of oxygen in the chamber atmosphere increases. For saturation diving, for depths greater than 54-65 m [6] the risk of fire is minimal, as these depths require an oxygen content of less than 6% in the decompression chamber. For saturation diving, oxygen concentrations above 6% will occur throughout the test range, and always during decompression. Inert gas concentrations, chamber pressure and humidity also determine the degree of fire hazard. Special hygiene, housekeeping and sanitation procedures were and are in place to mitigate the risk of fire. Hyperbaric facilities in the GWK-200 and fire-fighting equipment in the DGKN 120 were also installed, and a rapid evacuation to an adjacent chamber as an escape compartment was prepared at technical and organizational levels.

The greatest risks on the technical side are an uncontrolled drop in pressure p_k and the potential loss of control of the composition and state of the atmosphere due to the malfunction of the primary life support system. At the time, achieving the state-of-the-art safety (the level of safety is determined by the requirements of the classification societies' regulations) was very expensive. However, these are only requirements that do not precisely define the design assumptions of the classified components of diving systems. For example, the life support system was triple for each chamber with the addition of emergency capabilities through the installation of inhalers to isolate the divers' airways if the atmosphere gets contaminated. In addition, each chamber had internal carbon dioxide and moisture absorbers, and divers had individual carbon dioxide absorbers. The aforementioned devices and equipment were there to be used if external life support systems had to be cut off.

The safety system provided for giving access to a physician or an emergency exit from the chamber by the divers during all phases of the dive. An adequate supply of breathing gases was ensured for these operations.

Tab. 4

Saturation exposures reported by ZSN and TPP until 1994 [15].

YEAR	No. OF SATURATION EXPOSURES	SATURATION PLATEAU [m]	BREATHING AGENT	ORDERED BY:
1983-1985	6	5 - 20	Air	Szczecin Shipyard
1985	6	from 20 to 30 every 2	Nitrox	CPBR Szczecin Shipyard
1989-1990	16	30, 45, 50, 80, 100	Heliox	CPBR Szczecin Shipyard
	3	30, 40, 45	Nitrox	
1994	2	30	Heliox	KBN
Total	34			

EVALUATION OF RESEARCH AND VALIDATION OF THE POLISH DECOMPRESSION METHOD FOR SATURATION DIVING

A system of such dives was tested in 1988-1990 at the Department of Diving Equipment and Technology of Underwater Works (Polish abbr. ZSNiTPP) of the Naval Academy and implemented in diving units manufactured by the Szczecin Shipyard [Stocznia Szczecińska S.A.]. Thanks to the method of continuous decompression developed by the Department of Underwater Medicine of the IMM WAM and the research and construction teams of the Naval Academy, its time was reduced to a safe minimum. Decompression times according to this method are shorter than for the stepwise decompression commonly used in the world.

The developed system of saturation dives to a depth of 100 m, and the principles of medical protection for divers, successfully passed the quantitative minimum validation during exposure in the DGKN-120 chamber unit.

The following research objectives were adopted in the development of the 100 m deep saturation diving system:

- to provide the divers with maximum safety with regard to immediate and delayed consequences,
- to be able to work in the water more effectively than in conventional diving,
- to put aside so-called personal factors of susceptibility to pressure sickness when selecting the diving team for the research,
- to ensure proper physical and mental recovery in the chamber and overall regeneration,
- to check the design and technical performance of domestic diving equipment and facilities - the DGKN-120 and GWK-4200 complexes.

During the research, which also took into account the training dimension of the project, the divers spent a total of several thousand hours at elevated pressure.

The problem of effective and safe decompression from a state of full body saturation with trimix from a "depth" of 100 m, solved during these studies, can be counted among the most serious theoretical and applied achievements of underwater medicine in the country at that stage of diving development.

The systematics and description of the phenomena associated with decompression are complicated by the lack of precise measurement methods to monitor the processes occurring in the tissues of a living organism. The mathematical models used to describe decompression do not reflect what happens in the body during decompression, and will always provide us with an approximation. The decompression algorithm is the result of correlating experimental data with mathematical models of decompression. The occurrence of decompression sickness (DCS) symptoms is treated as a statistical phenomenon for all divers subjected to the same decompression procedure. When testing experimental decompression tables for a given validation method, we try to ensure that for decompression saturation dives:[16]

- the number of experimental dives is limited to the necessary minimum,
- based on existing experience, current knowledge and the adopted decompression model, the probability of pressure sickness was theoretically low,
- the outcome of the experiment gave an unequivocal answer as to the assumed safety confidence factor of the decompression method under study.

One of the limitations is the theoretical permissible supersaturation in the theoretical tissues. Therefore, during the experimental decompression, additional restrictions were imposed on the divers regarding adverse behaviour during decompression, i.e., the desaturation of their body tissues. The staff supervised so that during decompression, the test divers refrained from risky behaviours such as; rapid movements, physical exertion, remaining in an unchanged body position for long periods of time, cooling down, not taking in fluids and appropriate diet. A very important element was to ensure proper mental health by avoiding stress and conflict situations in the chamber. This applied to relationships between divers, divers - staff as well as divers - research staff. These situations sometimes could not be avoided, the reasons for which included imperfect match of test divers' character, individual attitudes, different individual reactions to inactivity caused by confined spaces. The divers' subjective assessment of the conditions in the chamber was not always based on the reality of the situation. For example, there were cases where two divers complained that the chamber was too hot and one reported that it was too cold. This was the effect of malice and the 'balance of power' in the chamber.

Experimental saturation diving was carried out in the DGKN-120 diving unit, equipped with prototype solutions for life support systems, and continuous monitoring of atmospheric parameters under pressure and helium-dominant atmospheres.

The decompression assessment was based on the assumption that only typical cases of pressure sickness of the first type, i.e., pain in any of the large joints, primarily the lower limbs, and therefore cases requiring medical intervention (administration of oxygen, recompression), would be the valuation criteria. Cases with different symptoms of questionable and transient nature would not be considered.

Tab. 5

Assessment of risk of pressure sickness incidence according to American researchers Weathersby, Honer, and Flyn for 1% and 10%, depending on the incidence of pressure sickness [16].

No. of dives	No. of cases of the sickness	Risk index 0.10 Confidentiality interval 0.99	Risk index 0.10 Confidentiality interval 0.90
1	2	3	4
5	0	0,95	0,59
	1	0,04	0,33
	2 and more	0,01	0,08
10	0	0,95	0,35
	1	0,09	0,39
	2 and more	0,01	0,26
20	0	0,82	0,12
	1	0,16	0,27
	2 and more	0,02	0,61
50	0	0,61	0,01
	1	0,31	0,03
	2 and more	0,08	0,96

The course of the trimix saturation diving followed the research objectives, the divers' daily schedules and the validated decompression programmes (decompression was started after a 35 - 57 hour stay at plateau).

During the exposure, some parameters of the gas environment deviated from the recommended values (the effect of these deviations on the decompression course was taken into account in subsequent exposures):

- deviations from the partial pressure of oxygen were greater than assumed and reached 3 - 5 kPa /± 6 - 10 %/,
- deviations from the desired temperature were greater than expected, up to 2 - 3ºC.

Other parameters or values were in accordance with the established requirements p_{abs}, p_{CO2}, relative humidity, mixture movement, toxicological and microbiological contamination [6].

A team of scientific and research staff from the Department of Maritime Medicine of the Military Medical Academy participated in the development and validation of the diving system and ensured medical protection of the exposures. The Polish system of saturation diving up to 100 m both from the technical and medical side successfully passed the quantitative minimum threshold during saturation exposures in the DGKN-120 diving unit.

Poland was among the few countries to have developed its own tables for saturation decompression despite the rivalry of the leading research diving centres at the time. These tables differed in basic parameters such as: rate of depressurisation, composition of breathing mixtures used, safety assessment methodology and organisational and technical considerations. Differences in decompression were influenced by the views and knowledge of underwater physiology in the countries concerned. In the development of decompression tables around the world, special role was played by the Armed Forces and centres that worked for the offshore industry (e.g., US, France, USSR, UK). The technology of saturation diving was considered a strategic technology, which implied limited information exchange. In Poland, the programme of research into long-term human stay under pressure brought together the research and implementation potentials of the Armed Forces, the shipbuilding and offshore industries, and technical universities, with the Naval Academy leading the way also when it comes to its potential for implementation.

DEVELOPMENT OF EMERGENCY MEASURES

At the time, published sources claimed that pressure sickness in saturation diving was about 10 times more common than in traditional diving. Fortunately, in 86% of cases these are mild (pain) accidents [16].

The causes of divers' exposure to pressure sickness can be divided into two groups. When these occur, appropriate technical and organisational measures have been prepared. The first is the incompatibility of validated decompression rates with the ability of the body to eliminate excess dissolved nitrogen. The consequence of this can be symptoms of pressure sickness type I. The probability of such an incident occurring is within the range of non-eliminable risk. Technical causes of exposure include: too rapid a rate of depressurisation, measurement errors in gas content (especially oxygen and carbon dioxide), harmful admixtures and low atmospheric temperature (which affects the operation of life support systems). Obviously, these negative factors would have to operate over a longer period of time, which was prevented by the increased medical-technical supervision, which translated into the organization and logistics through the duplication of maintenance and supervisory positions. If, in the course of saturation decompression, a deviation from the planned pattern (decompression rate, partial pressure of oxygen, temperature) were to be accidentally detected, further depressurisation would be halted, the extent of the risk would be analysed and, depending on the findings, a decision would be taken to initiate recompression, to stay at the same pressure or to resume decompression.

The second threatening factor is a sudden drop in pressure during decompression of a saturation exposure resulting from an operating error or technical defect. It involves a drop in the partial pressure of oxygen. Under these conditions, the diver's exposure depends on the speed and extent of the pressure change, and can lead to loss of life as a result of, among other things, rapidly increasing symptoms of pressure sickness. To eliminate such cases, we conducted trials and tests prior to saturation exposures and introduced design safeguards. This was realised by duplicating operational valves, airlock designs that precluded improper handling, by adopting the principle of separation of individual escape compartments. In addition, the inhalers were supplied with a special emergency mixture with elevated oxygen partial pressure for pressure sickness treatment procedures [17].

The treatment of a diver who develops pressure sickness type I symptoms during a planned saturation decompression depends on the depth at which these symptoms occurred. If it is less than 18 m, the inhaler system supplied with pure oxygen was used for a period of two 20-minute cycles breathing oxygen and 10 minutes breathing 20% heliox already at the depth at which the condition occurred, without recompression. If this proves ineffective, the diver is pressurised to relief pressure by administering oxygen and heliox.

In the event of pressure sickness symptoms at depths greater than 18 m, the diver should be compensated to relief pressure, or slightly above. The diver is compressed in 2 - metre pressure increments at a rate of 2 m/min with 3 minute stops at each decompression station. As a rule, a compression of 6 - 8 metres is sufficient in not severe cases, and the diver is left at this pressure for 2 hours. Decompression is carried out according to the previous scheme. During the treatment process, we should ensure thermal comfort to the diver and an additional 500 ml of fluids. If the diver is breathing pure oxygen, special attention should be paid to the possibility of developing a pulmonary form of oxygen poisoning and the magnitude of exposure should be determined using oxygen toxicity units.

In the event of a sudden drop in pressure in the chamber, divers should immediately evacuate to another compartment where they should be decompressed to the previous pressure. The period of the emergency pressure drop must be as short as possible and the entire operation from the time of the pressure drop to the return to the previous pressure must take no longer than 5 minutes. If a diver develops symptoms under these conditions, he is compensated with heliox to a pressure several atmospheres higher, under which he remains for a period of 30 minutes at a pO_2 of 120 kPa. From this pressure he is decompressed according to ad hoc schedules depending on what depth the incident occurred.

Resilience to failures and contingencies in the life support and measurement systems in the DGKN 120 complex from the point of view of safety theory was achieved through triple functional and structural redundancy. This allowed us to carry out decompression with assumed accuracy and to respond to malfunctions in the components of the diving complex.

In addition to the three external primary life support systems, DGKN-120 had emergency systems installed in the chamber. These included:

- internal CO_2 absorber with ventilator,
- breathing systems - inhalers (BiBS) to secure breathing from outside the chamber atmosphere,
- internal heaters.

In addition, individual CO_2 absorbers and warming kits for divers were prepared outside.

An independent supply of mixtures, inert gases and oxygen [14], was also maintained in case of an emergency to ensure that the chamber compartments were filled at least twice to the pressure prevailing on the plateau.

RESEARCH AND IMPLEMENTATION TEAMS

Experimental saturation dives were carried out in the DGKN-120 diving unit, equipped with prototype solutions for life support systems, and continuous monitoring of atmospheric parameters at high pressure. The main burden involved in coping with this difficult research problem rested with the scientific and technical team of the Department of Diving Equipment and Underwater Work Technology of the Naval Academy. They designed and built, in large part, a unique land-based diving unit provided with technical research solutions and equipment necessary for research purposes. A team of scientific and research staff from the Department of Maritime Medicine at the Military Academy of Medicine participated in the development and testing of the diving system and medical protection measures for the exposures. The ZSNiTTP secured the organisational side of the research taking care of specialist preparation and training of the test divers. This required formal solutions and logistical support for saturation exposures to be carried out at the right time. Divers spent a total of several thousand hours under pressure in a saturation state and during pressure training and adaptation exposures. The Polish system of saturation diving up to 100 m complied with quantitative validation minimum during exposures at the DGKN-120 diving unit.

Specialists from the Szczecin Shipyard, supported by scientists from the then Szczecin University of Technology, played a very important role. Thanks to the launching of domestic production of fittings and pressure installation components, it was easier to build safety systems for saturated diving complexes.

TEAM DEALING WITH TECHNICAL AND ORGANISATIONAL STUDIES

CDR Medard Przylipiak, the founder and head of ZSNiTPP, who developed a programme of technical studies of long-term human stay under pressure was a man with previous experience in the construction of chamber units. In the 1960s, he was one of the main designers of the naval rescue base in Indonesia, built by the Naval Shipyard. He also collaborated in projects at the Szczecin Shipyard in the construction of the Witiaź type research vessels, and with the Northern Shipyard [Stocznia Północna] in the construction of the diver's node on the Piast type ships. In addition, he was in charge of the Research and Development Division of the Naval Rescue Headquarters. Smooth delivery of the National Research and Development Plan [Polish abbr. CPBR] programmes was jeopardised when, at their very start, CDR Przylipiak unexpectedly passed away. Fortunately, the Szczecin Shipyard was very much interested in the programmes, and it was the Shipyard that forced the structures of the Naval School (from 01.10.1987 the Naval Academy) to continue their implementation. For the continuation of the programme, M. Pleszewski, who became famous for his design of the Błotniak-type submersible vehicle, was appointed the head of the ZSNiTPP. The late CDR Przylipiak organised a team of constructors based on the existing underwater vehicle construction and rescue team in the Ship Design and Propulsion Department and the staff and technicians from the Navy. They were looking for people from the diving industry. The authorities of the Academy, mainly through the networks of friends, recruited S. Skrzynski from the Maritime Rescue Centre. He was an officer with experience in deep diving with mixtures, who had worked with the Szczecin Shipyard, participated in the projects of the Maritime Rescue Centre, and in the construction of Piast type ships. In 1990, after a period of deployment, M. Pleszewski handed over the responsibilities of the Manager of the Department to S. Skrzyński, who continued his cooperation with the Szczecin Shipyard. He managed to partially reduce the debts owed by the Szczecin Shipyard to the Naval Academy.

The tasks under CPBR were divided between the following 7 executive teams:

1. The life support systems design and execution team developed:

a) regeneration systems,
b) chamber pressure maintenance equipment,
c) automatic oxygen partial pressure maintenance devices.

The core of the design section team consisted of the staff of ZSNiTPP and the Ship Design and Propulsion Department at the Faculty of the Technology of the Naval Academy, supported by external subcontractors. This group "brought up", among others, such well-known constructors of hyperbaric technology as M.Sc., Eng. Bartłomiej Jakus and Ryszard Pisula (who in the 1990s was chief engineer of the LSH - 200 diving complex at the then IMMiT).

2) The automation team developed and executed:
a) a system for the display and recording of saturation diving data,
b) measurement and automatic control of processes for maintaining atmospheric composition, as well as safeguards and warning signals.

This part of the project was carried out by scientists and design engineers from the Institute of Electronics of the Faculty of Technology of the Naval Academy, headed by G. Łowiec, M.Sc., Eng.

3) The diving apparatus laboratory of the ZSNiTPP developed and manufactured:
   a) decompression chamber inhalers with external exhalation (BIBS)
   b) individual carbon dioxide absorbers,
   c) electrical penetrators
   d) and prepared the test benches for their testing,

This was the team established from the inception of the Department under the leadership of J. Marek while the ideas originated from an outstanding technician of the diving apparatus S. Wisniewski.

4) The electronics laboratory of the ZSNiTPP developed and prepared:
   a) operating and astronomical time clocks,
   b) humidity measurements
   c) heat and humidity simulators and carbon dioxide dosing.

The team was headed by Sł. Chojnacki, M.Sc., Eng.

5) The hyperbaric chambers workshop of the ZSNiTPP dealt with:
   a) preparing, upgrading, and installing chambers and life support systems,
   b) preparation of saturation exposures,
   c) secured social needs of the diving team, service personnel and research staff.

This team was at first headed by Lieutenant Commander T. Wojczykowski, and after his departure the duties were taken over by Lieutenant Zbigniew Talaska. In this team, J. Pawlak, an electrician-electronics technician, who acquired computer skills and used them in a creative way, proved to be very creative. His knowledge and experience is still used today.

2) The gas mixture laboratory of the ZSNiTPP was entrusted with:
   a) preparation of the mixture installation
   b) storage of breathing gases
   c) pumping of breathing gases
   d) and the reloading base for pressure cylinders.

The team was led by CDR Kramer, who built the gas storage installations.

3) The gas analysis laboratory was involved in:
   a) developing measurement methods
   b) carrying out measurements.

The laboratory worked based on the equipment and a measurement engineering team from the Mine Rescue Centre in Bytom. The measurement technique was the responsibility of Lt. Ryszard Kłos, who developed the measurement methodologies and tested the sensors and measurement equipment. He also contributed to the training of the teams, not only the measurement teams, but also the test divers.

4) The service staff training team dealt with:
   a) training and servicing of the in-house staff,
   b) training and servicing of the external personnel,
   c) training and servicing of the technical staff of the shipyard,
   d) preparing the tester divers for their tasks and keeping them mentally and physically fit for diving.

This team was organised on an ad hoc basis, depending on the needs. Stanislaw Skrzynski supervised the execution of this task and was responsible for carrying out experimental saturation exposures and formal approval of the equipment manufactured by the Naval Academy to be used by divers. The first step for the Department's management team was to obtain civilian diving authorisations, which were formally required to conduct research with the participation of divers.

5) In addition, there was a finance and materials section at the ZSNiTPP, which kept its own books of accounts.

At that time, there were more than 40 people working at the Department and it is estimated that more than 100 specialists cooperated with them, including shipyard employees.

MEDICAL RESEARCH TEAM

Since the establishment of the Department of Diving Equipment and Technology of Underwater Works (ZSNiTPP), which had an equipment base and prepared technical staff, it lacked a 'strong' medical team. The cooperation with physicians was initiated by the founder of the Department, CDR Medard Przylipiak, and CDR Tadeusz Doboszyński, who was the head of the Underwater Physiology Unit of the Department of Maritime Medicine of the Military Medical Academy. Although these were research units with very different specificities, cooperation continued through the times of economic turbulence and organisational changes. In the programme of saturation diving research, these teams, being unique in the country, cooperated successfully. Prof Doboszyński was a pharmacist by training, and CDR Bogdan Łokucijewski, who accompanied him in the development of the medical programme, was a non-practising physician. Drs Romuald Olszański and Bogumił Filipek, from the Polish Army Divers and Scuba Divers Training Centre, were directly involved in providing security for the saturation exposures. They had a specialisation in maritime and tropical medicine, and Dr Olszański additionally specialised in dermatology. Among the most eminent continuators active to this day is precisely CDR Prof. Dr. Romuald Olszański, who conducted research during experimental dives to assess the probability of a decompression incident. This was original research on haemostasis parameters as an indicator for the evaluation of decompression systems and the interpretation of phenomena occurring during decompression. It involved blood sampling before diving and after decompression, which was cumbersome for divers. CDR Bogumił Filipek, on the other hand, measured harmful admixtures in the chamber's atmosphere during his watch. The aforementioned physicians were on continuous duty during the experimental saturation dives, which also allowed them to familiarise themselves in detail with the practices of handling the diving unit and to control the daily plan, as well as to carry out medical examinations. In addition, every day the divers completed medical questionnaires and were supervised by a psychologist.

A TEAM OF TEST DIVERS

Twenty-four tester divers took part in the aforementioned exposures. They had to meet the conditions set by the physicians taking care of diving safety; they could not have a history of diving accidents and be not older than 25 at the start of the research programme. They were recruited mainly from Szczecin's diving clubs and were selected, tested and supervised by the Department of Physiology at the Szczecin Medical Academy, headed by Professor Janusz Paradowski. Only eight test divers for the nitrox and air saturation dives were recruited from the Tri-city diving clubs and the age threshold applied to them was under 40 years of age. The Szczecin group was trained and selected after two practical courses delivered by ZSNiTPP, during which a depth of 30 m was reached at sea by diving to the historic wreck of ORP Smok. Training in the use of diving equipment and working in difficult conditions was carried out in Szczecin, at the swimming pools of the Szczecin University of Technology, adapted for working with tools in difficult conditions. The team was also trained on the new diving equipment used in the GWK-200 unit.

The team of test divers was shrinking, so that when it came to the shipyard trials it consisted of only six people. The loss of test divers was due to three factors. Most of them were students who, over time, finished their studies and their jobs did not allow them to continue as test divers. The second major factor was financial instability and interruptions in testing, which undermined continued participation. The third was the elimination of five people for psychological and medical reasons.

The team of test divers was supplemented by a group of three technicians seconded from the shipyard, who, being divers themselves, took care of training and organisational matters in Szczecin, as well as got prepared to fulfil the duties of service watch leaders during the test dives. They were also constructors, involved in the construction of elements of the chambers of the GWK-200 unit. The team of test divers was led by J. Waraksa, Z. Kamiński and, at the last stage, Z. Byrski. Divers Krzysztof Czermak, D. Różga, and M. Nosal took part in the shipyard's 100 m saturation diving trials. The first two are still active in the construction and repair of diving systems and installations, not only in our country.

The most important point was that participation in saturation diving tests did not affect the health of the tester divers. Several former test divers are still active today and they participate in commercial underwater work.

CONCLUSION

The Department of Diving Equipment and Underwater Work Technology at the Naval Academy has been involved in saturation diving for many years. It is, and was, the only institution in the country that carried out research programmes related to this subject. The political and economic situation in 1991, when the Soviet shipowner did not pay and abandoned the purchase of a series of diving units and specialised vessels, resulted in the collapse of production and skyrocketing debts. In many cases, it was also the cause of the bankruptcy of companies involved in the production of diving units for the Szczecin shipyard, which itself was in a critical situation. Specialised staff either changed jobs or sought work abroad. The Academy paid for this with a debt equal to more than its 18-month budget. On the other hand, the fruits of the research and implementation programme have been used by many scientists in Poland and abroad, sometimes without even mentioning the names of actual authors.

A negative development was the exodus of trained scientific, engineering and diving staff as a result of the radical deterioration of their economic status. This diving and technical potential will never be restored. The problem of brain drain particularly affected the Szczecin Shipyard, and to a much lesser extent the Naval Academy. The Academy was less affected because many people involved in this research were bound with the obligations of the army service. This allowed the selected scientific and engineering staff to be retained, and their experience and skills to be utilised. Only a minimal line-up was left of the team carrying out this work and they continued working not only in research but also commercial context.

Despite such negative developments, experience and knowledge have not been lost. Thanks to the academics, engineers, technicians, and diving personnel who remained in the diving research realm, the knowledge gained was and is being deployed in the national economy and defence. It is also not without significance that the knowledge and experience gained have been passed on to the next generation of scientists and technicians dealing with underwater work. A spectacular success of this transfer of research experience gained in 1981-1991 is the fact that since 1995 our country has been independent from foreign underwater services using saturation diving, and has undertaken the production of many components of diving technology.

Poland was among the few countries to have developed its own saturation diving tables under conditions of competition among the then leading diving centres. These tables differed in basic parameters such as the rate of depressurisation, the composition of the breathing mixtures used, the safety assessment methodology, as well as organisational and technical considerations. Differences in decompression were influenced by views and knowledge of underwater physiology in the countries concerned. In the development of decompression tables around the world, it is important to distinguish between centres of the Armed Forces and centres that worked for the offshore industry (e.g. USA, France, USSR, UK). The technology of saturation diving was considered a strategic one, which implied limited information exchange. In Poland, the programme of research into long-term human pressure diving brought together the research and implementation potentials of the Armed Forces, the shipbuilding and offshore industries, and technical universities, with the Naval Academy leading the way as the only actor having sufficient potential for implementation.

The saturated exposures provided the basis for enhancing the scientific qualifications of the universities and research centres participating in these programmes, which resulted in 6 Ph.D. theses in engineering and medicine and 3 habilitations. In the author's opinion, however, more important than the development and scientific achievements in the practical sphere was the training of design, engineering and diving staff, whose output we still benefit from today. This was, and still is, reflected in the international scientific and defence cooperation that took place over the next 30 years, and in the use of the intellectual, technical and organisational potential gained for the needs of the national economy. The investment in what is important in diving, i.e., practical skills, has more than paid off. This is confirmed by the implementation and daily practice of saturation and deep-sea diving for commercial applications in the next decades of the changing reality in our country.

In part three of the series of articles on Polish solutions, research and application of saturation diving, the author will focus on how these dives have been carried out in our country.

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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