

PRELIMINARY TECHNICAL RISK ANALYSIS FOR HELIOX TRAINING SATURATION DIVES CARRIED OUT IN KTPP AMW PART II

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ABSTRACT

The safe implementation of saturation dives in KTPP AMW¹ in accordance with the plan of professional development in SZRP realised at the experimental deep-sea diving complex DGKN – 120² requires an assessment of potential inherent technical risks in order to identify, quantify and prioritise potential hazards of the saturated hyperbaric exposure process. The process is impacted by a considerably vast number of factors, the relative values of which should be kept at an acceptable level. In certain cases, even despite corrective measures, control over them may not be optimal and fully implemented. In such cases, the elements in question become elements of the residual risk of the saturation exposure process using the DGKN-120 habitat. An acceptable level of safety for diving using technical means should be guaranteed and the hazards identified during an iterative and systematic analysis of the residual risk of the process under consideration.

Keywords: risk analysis, saturation dives, diving mixes.

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INTRODUCTION

This article is a continuation of the risk analysis which was the subject of its first part published in the previous issue of *Polish Hyperbaric Research*. The analysis of the technical risk of hyperbaric exposure in the *DGKN – 120* complex was carried out within the framework of the scientific and research work entitled: TULIPAN V No. DOB-BIO-12-03-001-2022 stage1.task.2 in the Department of Underwater Works Technology at the Faculty of Mechanical and Electrical Engineering of the Naval Academy in Gdynia.

As mentioned earlier, the approach resulting from the risk analysis using the *FMEA*³ method does not define ready-made solutions for how a given defect should be removed, but only indicates critical elements of the process at the stage of diagnosis and assessment of the risk of potential errors occurring. By its very nature, the assessment is subjective, as each team individually assesses a given risk based on its own knowledge and experience. All risks identified in the first part of the article have been given high priority. The proposed solutions should aim to reduce each of them down to medium and as low as possible.

Eight risks were initially described in Part One:

- loss of control over oxygen content;
- loss of control of carbon dioxide;
- contamination of the chamber atmosphere;
- loss of control over temperature;
- loss of control over humidity;
- loss of control over depth;
- fire in the hyperbaric complex and the hyperbaric chamber room;
- emergency decompression;

In the second part of the article further five identified risks of the hyperbaric exposure process are analysed:

- breathing mix reserve;
- breathing mix quality;
- failure to maintain the compression schedule;
- failure to maintain the decompression schedule;
- evacuation from the hyperbaric complex.

The study followed the numbering of identified threats in a manner that was adequate and consistent with the order listed in the first part of the paper.

PROCESS ANALYSIS

RE. 9 INSUFFICIENT BREATHING MIX RESERVE

The preparation of an adequate supply of breathing mixtures, and determining the saturation depth, treatment or short-term exposure along with the planned duration is the core of starting to plan gas requirements. In *KTPP AMW*, cylinder quads and fixed tanks with a capacity of $V_z \approx 1 \text{ m}^3$ and an operating pressure of $p \leq 15.0 \text{ MPa}$ are used for gas storage. Such low storage pressures are not recommended, therefore mixtures in storage tanks should be kept at a pressure of at least $p = 20 - 30 \text{ MPa}$.

The *DGKN – 120* diving complex consists of three chambers with a total geometric capacity of $V = 43 \text{ m}^3$. During the preparation stage, it is necessary to ensure the necessary amount of essential, emergency and therapeutic breathing mixtures for filling the

hyperbaric complex and for daily consumption. The amount and type of mixtures depends, inter alia, on the compression method, saturation depth, volume of the hyperbaric complex, number of divers, etc. During the stay, due to current consumption and losses of the mixture during sluicing and transfer, it is necessary to replenish the composition of the habitat atmosphere. When performing long-term underwater works, the supply of breathing mixture in the gas storage facility must, in accordance with applicable regulations⁴ enable three divers to stay below the surface of the water at the maximum diving depth and at a maximum ventilation equal to $50 \text{ dm}^3/\text{minutes}$ for 8 hours and ensure that the hyperbaric complex is filled at least twice with breathing medium to the pressure of 7 atm,⁵ and the diving bell at the maximum diving depth⁶. The amount of Hx and He ⁷ mixtures stored in the reserve should be separated into a reserve for the dive and an inviolable reserve for emergencies (e.g. sudden loss of depth, unsealing of the habitat, etc.). Each time divers are in the chamber, it is recommended to measure the gas composition with an analyser and assess the oxygen content before dosing into the chamber in order to avoid unintentional administration of pure inert gas or a mixture with too low oxygen content.

The calculations should also take into account the necessary emergency mixtures for the *BIBS* system, treatment mixtures, the supply of which should be sufficient to secure treatment at any planned diving depth of a given exposure. As is known, during a dive the atmosphere is subject to regeneration consisting in: removing the emerging CO_2 , water vapour and other contaminants, heating or cooling, and replenishing O_2 . It is therefore necessary to take into account the daily demand for O_2 for replenishing the atmosphere of the hyperbaric facility during compression, decompression and stay at the saturation plateau depth. The standard O_2 demand per diver is assumed to be $Q_{O_2} \approx 0.7 \text{ Nm}^3/\text{day}$ ⁸. The planned reserve for metabolic consumption and decompression should be doubled at the planning stage and kept as an essential reserve.

In short duration air exposures, at least two independent systems for compression and filtration of breathing air stored in independent tanks should be ensured in an amount adequate to that required by current safety regulations at *SZRP* [1]. Comparatively, according to *IMCA*, sufficient compressed air should be available to compress the decompression chamber to the maximum possible treatment depth (usually $50 \text{ mH}_2\text{O}$) plus enough air for three full decompression cycles. In addition, a constant supply of oxygen in an amount of at least 90 Nm^3 should be secured in the event of an implementation of emergency procedures. These recommendations cannot be applied to saturation diving and are therefore provided for comparison purposes only. They do, however, carry important information in the event of securing the diver's treatment post saturation. In this case, in addition to air and oxygen, it is also recommended to maintain the nitrox Nx 50/50 necessary for treatment at the maximum depth of therapeutic exposure of $h = 50 \text{ mH}_2\text{O}$.

In summary, the gas supply should include the amount needed for:

- compressing the habitat with the breathing mixture;
- supplementing oxygen for the divers'

- Metabolism⁹ in the chamber;
- supplementing gas necessary for sluicing and transfer to and from the habitat, diving bell¹⁰;
- supplementing the gas needed for compression of safety divers;
- supplementing the gas for compression of medical staff;
- supplementing of oxygen for diving, including decompression;
- supplementing of gas for excursions from saturation plateau;
- gas consumption by divers from *BIBS*;
- gas supply for medical treatment;
- emergency gas supply;
- regulatory gas supply (reserve).

Impact level after the materialisation of a hazard related to insufficient supply of breathing gas during hyperbaric exposure due to: failure of the depth maintenance system and pressure changes, failure to comply with applicable diving procedures, failure and sudden loss of sealing of the chamber or of a sealing of a chamber component, accidental leakage of storage tanks, damage to supply hoses or valves, or leakage of the regeneration system is high and has been rated at a relative level of $I=8$ on a ten-point scale. The effect of the materialisation of this hazard is a direct impact on the diver's health which, if not compensated for, may lead to a violation of the decompression schedule and create a potential risk of *DCS* and *CNSyn*, barotrauma, hypoxia. Emergency situations may result in a significant loss of the breathing mix supply which, in extreme situations, may be very dangerous and lead to a reduction and/or depletion of the stored supply. Therefore, planning the gas supply for the exposure to the extent necessary to achieve the objective, understood as meeting the needs arising from: compression and its interruption, standard and accelerated decompression, treatment during and after saturation, and diving at the plateau, emergency supply, personnel and equipment transfers, habitat ventilation, life support and calibration of measuring devices is crucial for the successful completion of a diving task. A redundant supply of breathing gases is usually maintained at a relatively low pressure of $p = 12.0 - 15.0 \text{ MPa}$. Furthermore, due to the diversity of gases used for diving, securing an adequate number of transportable diving cylinders¹¹ for storing emergency, medical and decompression mixtures poses a major challenge. The organisation of the dives required compensation for many logistical limitations and difficulties resulting from this and was burdensome for the saturation manager and the diving team. For this reason, the probability of a hazard occurring was estimated at a medium level and, on a relative ten-point scale, it was determined to be $P = 7$. The probability of detection was estimated to be as relatively medium, i.e. $98\% > D\% \geq 99.7\%$, which corresponds to the relative value of $D = 7$ on a ten-point ordinal scale. The value of the relative risk number in this case is at the level of the cumulative value $RPN(SOD) = 392$, exceeding by about 3 times the critical value $RPN_{kr} = 100 - \text{tab. 3}$. As a way of responding to the risk, an effective safety device was provided to automatically control the closing and opening of the isolation valves on the chamber jacket in case of a system leak, and an additional five transport quads were ordered to store the amount of breathing mixtures necessary to secure the

dive. It was also recommended that the breathing mixtures be prepared and that the pressure in the storage tank be kept as high as possible, i.e. $sp > 15.0 \text{ MPa}$, in accordance with the compilation indicated in the compiled list of gases planned for use in saturation dives.

This lowers the relative probability of the risk materialising, to an unlikely level, estimated at the relative level $P = 4$ with the addition of four more quads there is the possibility of a further reduction to $P = 4$ and an increase in the probability of detection to full, due to the gas loss protection system and the increase in the quantity of breathing mixes: $D = 4$. This allows the risk number to be reduced to $RPN(SOD) = 160 > 100$ lying slightly above the critical value.

The risk at this level, as residual, should be accepted and continuously monitored by striving to ensure redundancy of diving quads remaining at disposal. A high value of $SEV = 8$ defines the need to ensure that the risk has been taken into account following risk reduction and that preventive measures are sufficiently effective. A high value of $SO = 56$ value indicates which hazards are likely to be the most common. Some organisations recommend focusing primarily on the severity of their occurrence, which seems appropriate where high human safety is extremely important. SO is the product of the severity of a hazard and the probability of its occurrence, thus the focus should be on reducing its numerical value by minimising the value O and then implementing full detection, resulting in an acceptable RPN level

Preliminary analysis of the technical risks of hyperbaric exposure.

Type of problem/problem situation	Risk materialisation impact	The severity of impact after materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Probability of detection of risk materialisation	Probability of detection of risk materialisation	RPN	The countermeasure applied against risk materialisation	Corrected RPN			
		SEV		OCC		DET			S	O	D	RPN
1	2	3	4	5	6	7	8	9	10			
Insufficient supply of breathing medium	Potential accident, risk to the diver's health and life	8	Operator error, sudden loss of depth, fire, habitat leakage and ventilation, loss of gas supply in storage tanks, failure of depth maintenance and regeneration system. Shortage of transportable dive quads. Low gas storage pressure.	7	Possible average detection	7	392	Minimisation. Purchase of additional diving quads, increase in storage pressure of diving mixtures, protection of habitat against unsealing - cut off automatic valves, planning - full set of breathing mixtures to secure the exposure	8	5	4	160
Poor quality of a breathing mixture	Potential accident, health risk for the diver	10	Fire, loss of habitat integrity, operator error and non-compliance with SOP, inadequate quality control of breathing mixtures, misqualification of measurement systems for process monitoring, lack of an "a priori" online control	7	Possible average detection	6	420	Reduction. Training and adherence to SOP, qualification of measurement systems and measurement system operators, implementation of qualitative-quantitative methods for instrumental analysis of breathing gases, retrofitting of chemical analysers, redundancy of the automated online measurement system for the composition of the habitat atmosphere, detection of harmful contaminants in breathing air, measurement of oxygen concentration on the main line of the habitat supply and BIBS, avoidance of inert gases for compression/labelling.	10	5	2	100

Tab. 3 cont.

Preliminary analysis of the technical risks of hyperbaric exposure.

Failure to follow the compression schedule	Potential accident	7	Possible random event, operator error, gas substitution, fire, diver accident, rapid compression, leakage	5	Full detection possible	3	105	Acceptance. Habitat leak tests, breathing from <i>BIBS</i> to 10mwc, implementation of emergency compression stop and dive withdrawal methods. Treatment procedures.	7	4	3	84
Failure to follow the decompression schedule	Potential accident, health risk to the diver	8	Possible accident, operator error, loss of breathing mix supply, , <i>CNS</i> , <i>DCS</i>	5	Possible average detection	6	240	Compensation and monitoring. Decompression schedule, acoustic indication of decompression time, alternative plans in case of <i>CNS</i> and loss of breathing agent supply <i>SOP</i> - records. Treatment procedures.	8	4	4	128
Evacuation from the hyperbaric complex	Potential accident, risk to the diver's health and life	8	Possible accident, malfunction, operator error	3	Possible average detection	6	144	Acceptance active, monitoring. Emergency evacuation plan - treatment after: interruption of saturation, evacuation to another chamber, skipping decompression. Modification of <i>SOP</i> , establishment of protection in <i>RLKZH</i> , air, <i>O₂</i> and nitrox <i>Nx</i> 50/50	8	2	6	96

RE. 10 POOR QUALITY OF THE BREATHING MIX

The vital aspect of maintaining safety during underwater work and the use of diving equipment is the quality of breathing gas. It also has a significant impact on the development of technologies for the distribution, production and quality control of breathing air in hyperbaric facilities. The need to maintain high quality air and breathing mixtures in the Armed Forces of the Republic of Poland stems from the provisions of applicable national normative requirements: NO-07-A005:2020(2), NO-52-A201:2012,(3), safety regulations in force in the Polish Armed Forces(4) and NATO¹² standardisation documents, AdivP-04 (5)(6). According to the recommendations in the Polish Armed Forces, users should perform tests confirming the quality of the breathing mix every 3 months or 50 *hours* of operation of the compression and filtration system. Similarly, in commercial civil diving, these requirements are regulated by the provisions of the Regulation of the Minister of Infrastructure of 19 May 2004 on occupational health and safety during underwater work (Journal of Laws 2004.116.1210¹³ [7]. Unlike the provisions laid out in the Polish Armed Forces Regulations, they require physical and chemical composition tests to be carried out every six months to confirm their continued suitability. This aspect is also regulated by the requirements of PN-W-88503:1998/Az1:2000 and PN-EN 12021:2014-08. During saturation diving, the diving supervisor and operators should systematically measure the main components of the gas and the trace contaminants required by the regulations. During diving, the oxygen and carbon dioxide levels should be routinely monitored. This does not exclude the detection of other gases such as carbon monoxide, etc.

It has been demonstrated that even the implementation of modern redundant compression and filtration system solutions does not ensure adequate production process capacity. It was found that even the most modern filtration systems are not immune to the effects of operator non-compliance with SOPs¹⁴, such as the suction of difficult-to-remove contaminants, loss of filter bed properties, etc. [10]. The current state of the art in operating conditions without the use of appropriate control systems does not allow for the achievement of a higher than 3σ capacity of the process of obtaining, maintaining and distributing breathing air intended for hyperbaric conditions [11].

The need to ensure proper air quality for hyperbaric exposures, requires fitting qualification and metrological supervision of the measurement systems in use [12,13]. From the point of view of toxicological and technical risks [14], the safe and effective implementation of hyperbaric exposures is governed by the control of numerous dynamically changing parameters of the composition of the atmosphere, including the proportion of harmful contaminants. A risk assessment analysis of the process [10] has shown that for the current best available technology for obtaining, maintaining and distributing breathing air for hyperbaric oxygen conditions, the greatest potential lies in safety systems, either in a simple form¹⁵, or in the form of systemsⁱ equipped with multidimensional sensory systems,ⁱⁱ expert systems and actuators¹⁶ [11,15]. It is believed that the implementation of *online* control systems will reduce the risk of process defects materialisation. Conducting proper inference and control of the production processⁱⁱⁱ requires the use of

a reliable and usable surveillance tool with proven metrological properties, without which achieving high process capability in the production of breathing mixes is not possible. The use of adequate measuring equipment is an important element influencing the safety of underwater work, minimising the potential toxicological effects of the contaminants present on the diver's organism. The *ad hoc*^{iv} use of indicator tube systems or other portable analysers is insufficient. Their use often leads to erroneous inference and misinterpretation of the measurement results obtained and, consequently, the status of the supervised process. Portable gas analysers in use and automatic warning systems implemented in filtration systems allow only partial control.

According to the requirements of PN-EN ISO 10012 [16], an effective measurement management system should ensure its suitability for the intended use and have a significant impact on the achievement of product and process quality objectives, and should therefore meet critical quality requirements *CTQ*²¹. Accumulating an adequate supply of breathing mixtures is very important, but without a reliable quantitative and qualitative assessment of the composition of the main analytes and trace admixtures, it is completely useless. The main criteria for assessing a measurement system intended to be used for process monitoring with a view to ensuring adequate assessment capability are the usefulness and reliability of the measurement system for the intended use. Usefulness is understood as the system's ability to measure data within defined process tolerance limits while maintaining the required stability over time.

The reliability of a measurement system, on the other hand, should be considered as the degree of accuracy with which the approximate value measured by the system reflects the actual value. From the point of view of toxicological and technical hazards, the safe and effective implementation of hyperbaric exposure is determined by the control of numerous, dynamically changing parameters, including the measurement and control of standardised main components of the atmosphere and the presence of trace harmful contaminants [17]. Incorrect analysis fraught with error can lead to: poisoning by carbon monoxide, carbon dioxide (hypercapnia), oxygen in neurological (hyperoxia) and pulmonary forms, narcotic effects of gases (*HPNS*²² or nitrogen narcosis), hypoxia, asphyxiation (asphyxia) and, in the case of open water diving, poisoning by hydrogen sulphide²³ or hydrocarbons(oils)²⁴ [6,18,19].

Leaving aside the very important aspect of the qualification of measuring systems for process monitoring, there are known cases of operator error involving filling the habitat compartment space with gas of the wrong composition. Such an example would be inadvertent dosing of an inert gas into the chamber in the form of pure helium. Such a phenomenon is extremely dangerous and is critical because of the possibility of materialising a risk to the life and health of the diver in the habitat. The accidental supply of pure inert gas to divers in diving practice has already resulted in several fatalities. The inhalation of pure inert gas leads to the immediate flushing of oxygen from the diver's tissues, causing immediate collapse followed by instant death. In such a case, there is little chance of effective resuscitation. It appears that accidents of this type can result from failure to follow gas connection procedures and perform

analysis prior to use. Because of the serious consequences of such accidents, it is recommended that the inert gas in the gas storage be replaced by a mixture containing at least 2% oxygen for a given depth of 50-150mH₂O. At a depth of 50mH₂O oxygen partial pressure of $p_{O_2} = 12kPa$ will cause the diver to lose consciousness, but will not lead to death. At depths less than 50mH₂O, where the inert gas may be helium or nitrogen, a concentration of 2% is not sufficient, and a higher percentage of oxygen must be added to the inert gas. For this reason, in the gas use schedule, the minimum oxygen content of the inert gas will be given before carbonation begins. Pure inert gas may be needed in exceptional circumstances, e.g. in the case of a very deep saturation plateau or ventilation of the chamber in case of fire. In this event, strict procedures must be in place for the transport, analysis, connection and use of inert gas. The decision to use inert gas must always be confirmed by the dive leader and the cylinder marking and description must be unambiguous.

Much more sophisticated analytical equipment, such as mass spectrometers or gas chromatographs, may also be used in the course of analysis where possible. Measurements of the composition of mixtures should be carried out by qualified operators in authorised laboratories²⁵ using measuring instruments and systems that should ensure the correctness of the measurements²⁶. Measuring instruments or systems require calibration²⁷ using etalons (working measurement standards²⁸) [20]. For the calibration of measurement systems, reference should be made to their correct value²⁹ (using measurement reference standards³⁰) which is an assigned and recognised value³¹, determined with an acceptable level of uncertainty³². This allows to maintain³³ the appropriate capability of the measurement system³⁴. When evaluating a measurement system, absolute reproducibility and repeatability for the standard, the measurement system and different operators must be taken into account [21]. It is recommended that testing laboratories authorised in the Polish Armed Forces should be accredited for the tests performed³⁵ and meet the requirements of PN-EN ISO/IEC 17025:2018-02. For this reason, tests have hitherto been performed in the Laboratory of the Marine Technology Workshop in Gdynia of the 1st Regional Logistic Base in Wałcz, which has recently been decommissioned for a period of 2 years thus leading to the collapse of the system for assessing the quality of diving breathing mixes in the Polish Armed Force. The materialisation of this risk seemed improbable but indicated that reliance solely on the measurements of the *WTM* laboratory of the *1RBLog* in Gdynia was short-sighted. *COL* did not provide alternative solutions in case of similar events, thus the construction of an independent redundant system became a necessity. No provision was made for alternative measurements in laboratory facilities as required by *GLP*. The proposed performance of measurements in external institutions was not accepted by the Naval Academy to the lack of fulfilment of the qualification conditions [22] of measurement systems and the use of inadequate and burdened measurement methods³⁶ without simultaneous quality control. This kind of measurement implementation cannot be accepted.

The severity of the impact of the materialisation of the risk due to improper quality of the breathing gas or incorrect use of the mixture during exposure arising from: inadequate measuring systems, operator error,

uncontrolled depth change, failure to comply with applicable diving procedures is very high and has been set at a relative level of $I=10$ on a ten-point ordinal scale. The effect of materialisation of this risk, depending on when it occurs, is the lack of possibility to perform dives, including experimental dives, and the failure to complete the project task, or a direct negative impact on the diver's health, which, if not compensated for, may lead to serious consequences, including life-threatening situations, e.g. due to suffocation, poisoning, etc.

Similar emergency situations may occur when measurement systems are incorrectly classified. Often, the differences in readings lead to discrepancies in interpretation by the diving safety team. It is important to be aware of the processes occurring in the habitat and to assume that every measurement system is subject to variability, which may be caused, e.g., by the measurement system itself, the operator³⁷ or the environment. These sources should be identified, understood, quantified and then compensated and controlled by the system operator.

For this reason, the probability of a risk was estimated at an average level and, on a relative ten-point ordinal scale, was defined as $P = 7$. The probability of detection was estimated to be as relatively average, i.e. at $98\% > D \geq 99.7\%$, which corresponds to the relative value of $D = 7$ on a 10-degree ordinal scale.

The relative value of the number of risks in this case is at the level of the cumulative value of $RPN(SOD) = 420$, exceeding the critical value $RPN_{kr} = 100$ – by about 4 times, tab. 3.

As a response to the risks involved, training for operators of measuring systems and breathing mixture preparation has been implemented, along with a strict list of gases planned for use in saturation, strict regulation and labelling of inert gases, and avoidance of their use unless clearly necessary. The ability to perform measurements with qualified³⁸ measurement systems independent for each compartment of the chamber in terms of measurement of: depth, oxygen and carbon dioxide concentration, temperature and humidity was complemented by the use of chemical indicator methods for the detection of: *CO*, *CO*₂, *H*₂*S*, *C*₆*H*₆ and hydrocarbons (oils)³⁹, and the use of instrumental chemical analysis of the breathing gases using gas chromatography methods for the determination of: helium, oxygen and nitrogen concentrations and mass spectrometry for the detection of undesired trace contaminants. Redundancy of measurement systems was used by implementing:

- measuring arrays and automatic systems;
- online analyses of oxygen on the supply line of the breathing mixture of the habitat;
- online analyses of oxygen on the supply line of the *BIBS* system;
- online analyses of breathing air from compression and filtration systems - developed in *KTPP AMW* indicator measurement system *BAPCS*⁴⁰;
- additional portable analysers, so-called *back-up*⁴¹;
- chemical analysis;
- instrumental analysis.

The need to introduce chromatographic analyses for the implementation of training saturation dives and the qualification of heliox mixtures for their use has been necessitated by the lack of possibility to perform

laboratory analyses by the *WRTM 1Rblog* in Gdynia. Providing an alternative means of determining the composition of breathing mixtures is critical to maintaining the ability of *KTPPAMW* to secure saturation dives. This reduces the relative probability of the risk materialising, to an unlikely level, estimated at the relative level of $P = 5$, and increases the probability of detection to full $D = 4$. This reduces the risk number to $RPN(SOD) = 100$.

The risk at this level as residual should be accepted and continuously monitored.

RE. 11 FAILURE TO MAINTAIN DECOMPRESSION SCHEDULE

The task of compression is to safely reach plateau depths and to stabilise the parameters of the breathing atmosphere so that it is safe for divers. The main risks during the compression process at high saturation depths are the induction of pain symptoms in the connective tissue and *HPNS*⁴² manifested with paralysis of the central nervous system *CNSyn*⁴³ [23]. Both effects arise from the interaction of high pressure with rapid compression, which limits the rate of reaching saturation plateau. Slow compression has the added advantage that if divers feel well afterwards, they can proceed immediately. However, their 12 – 24 hour acclimatisation at the saturation plateau depth is recommended. The decision to proceed more quickly can only be made by the physician securing the dive at the request of the dive leader. During compression, the aim should also be to accurately obtain and maintain the planned saturation plateau parameters⁴⁴. Depending on the method of compression, if the starting *Hx* mixture has an oxygen content less than 16%_v, divers use *BIBS* from the start of compression and breathe an emergency mixture e.g. *Hx*⁴⁵ containing 21%_v oxygen. The emergency mixture in the *BIBS* during the compression phase should be adequate. For this purpose, it is possible to use various *Hx* mixtures for which the partial pressure of oxygen is $p_{O_2} \in [16, 125] \text{ kPa}$. It should be remembered that there is always a potential risk of leakage when breathing from the habitat atmosphere once compression has started. This may cause an uncontrolled drop in the habitat pressure and consequently in the oxygen partial pressure to a dangerous level. Therefore, the compression should be stopped at a depth of 1 – 2m H_2O to check for potential leaks. The first phase of compression and pressurisation should be carried out using a mixture with an oxygen content safe for divers. If this is not possible, divers should use the *BIBS* to a minimum depth of 10m H_2O , until a safe level of oxygen partial pressure is reached in the habitat (homogenisation). Moreover, attention should be paid to the nitrogen content in the habitat as its high partial pressure could have an adverse effect on decompression. During compression, the regeneration system should be activated to improve the atmosphere homogenisation conditions. After reaching the depth of change of the starting *Hx* mixture, the supply should be changed and the compression of *Hx* should continue while controlling the parameters of the atmosphere composition up to the saturation plateau depth at the specified rate. During compression it may also be necessary to interrupt the compression and withdraw to the surface e.g. as a result of a diver accident preventing the dive from being continued. When the maximum depth and time of stay under pressure do not exceed the limits

for the *Hx* table for deep dives, it is possible to stop the compression⁴⁶ and return to the surface during compression using *the US Navy* tables [24]. In order to select the emergency decompression method, the maximum time for the diver to stay at the maximum depth reached should be determined⁴⁷. For information, limitations on the time spent at the maximum depth are given with regard to oxygen partial pressure p_{O_2} ⁴⁸ in the inhaled *Hx*. If oxygen decompression is not possible, it is possible to implement two alternative decompression schedules. One is air decompression. However, it is not recommended due to its long duration. An emergency air decompression table is used when oxygen or *Hx* cannot be used during emergency decompression after compression has stopped to saturation plateau. The recommended method is to switch to decompression using emergency *Hx*. The condition for using emergency *Hx* is that the oxygen content must be above $C_{O_2} \geq 16\%_v$. Emergency *Hx* decompression tables should only be used when oxygen cannot be supplied. This is the case in the event of a failure of the oxygen system, loss of oxygen supply or during the occurrence of dangerous symptoms of oxygen poisoning in the diver.

The intensity of the impact of the possible materialisation of the risk associated with habitat compression is moderate and equals to $I = 7$ on a relative, ten-point ordinal scale. Due to the adoption of the practice of using *BIBS* in the initial phase of compression, checking the tightness of the habitat before⁴⁹ and during compression (at a depth of 1 – 2m H_2O) and implementing methods for emergency stopping of compression and withdrawal, the probability was estimated at a low level and on a relative, ten-point ordinal scale it was defined as $P = 4$. The level of risk detection was estimated to be possibly full, i.e. $100\% > D\% \geq 99.7\%$, which corresponds to the relative value of $D = 3$ on a 10-degree ordinal scale. The value of the relative risk number in this case is at the level of the cumulative value of $RPN(SOD) = 84$, tab. 3. The risk at this level can be considered compensated and should be accepted as residual and monitored. This results in a reduction in the relative probability of the risk materialising, to an unlikely level, estimated at the relative level of $P = 4$ and an increase in the probability of detection to full, due to the expected alarm signalling of an exceedance of a control parameter with early notification of a likely exceedance of the tolerance limits: $D = 3$. This allows the risk number to be reduced to $RPN(SOD^{50}) = 108$, lying below the critical value.

The risk at this level as residual should be accepted and continuously monitored through control intensification, continuous and successive actions⁵¹ leading to a reduction of risks through continuous correction of the rationalised process. The product $SD(RN) = 27$ ⁵² obtained following hazard compensation still indicates that the ideal detectability of defects, which are the most dangerous (critical) for diver safety is not reached. Normally, using only the limit values of *RPN* to determine the need to implement preventive actions to avoid the potential materialisation of risks is unacceptable and not a recommended practice. Priority should be given to considering high values $S = 9 \div 10$, making sure that risks are taken into account e.g. in the design (Robust Design, Design Controls) or consider implementation of preventive measures in the process under supervision. The next step is to take into account the risks for which $S \leq 8$ has been defined, prioritising the causes with the highest possible incidence O ⁵³ and

then those with the worst possible detection D^{54} . It is useful to sort $RPN(SOD)$ according to the *PARETO* principle.

RE. 12 FAILURE TO MAINTAIN DECOMPRESSION SCHEDULE

Decompression may be commenced in a similar way to a permitted excursion to a depth less than the saturation plateau. The rate of progression to this depth is limited to $2 fwc \cdot min^{-1} \triangleq 0.6 mH_2O \cdot min^{-1}$. Undertaking decompression as soon as the permitted excursion depth is reached increases the risk of *DCS*, when the saturation plateau was at the level of $H \leq 60.6 mH_2O$. Therefore, in this case a 2-hour decompression stop at the depth of the permitted excursion from the saturation plateau is required. After this time, further decompression may be undertaken according to the diving technology.

Alternatively, the process of returning to normobaria can be started as a regular decompression procedure without the use of an initial diver transition to the depth of the permitted excursion, i.e. as in short dives. Decompression can be carried out continuously with a non-extendable rate of change of depth of $\dot{v} \leq 0.3 mH_2O \cdot min^{-1}$ or in increments, every $0.3 mH_2O^{55}$ according to technology requirements.

With continuous decompression, attention should be paid to the rate of decompression – the change in depth as a function of time. It should be systematically verified especially in automatic systems that cannot be left unattended. In the case of unscheduled decompression stops, the duration and depth of the stop should always be recorded so that the time of the stop can be included in the daily decompression schedule.

As it is difficult to maintain airtightness close to the surface, for example, the final decompression stop may be used before reaching the surface at a depth of $1.2 mH_2O$. In this case, the stop should last $\tau = 80 min$, and then the diver's ascent to the surface may be continued at $\dot{v} = 0.3 mH_2O \cdot min^{-1}$. During decompression, the oxygen partial pressure should be maintained at all times at $p_{O_2} \in [44; 48] kPa$, until the oxygen content of the complex reaches $x_{O_2} = 19\%_v$. From this point onwards, the concentration value should be maintained within the range of $x_{O_2} \in [19; 23]\%_v$. In order to prevent a sudden drop in oxygen partial pressure during the pre-deployment procedure to a decompression station equivalent to the depth of the permitted excursion, the partial pressure of oxygen in the habitat should be raised to $p_{O_2} = 60 kPa^{56}$ one hour prior to procedure implementation. The partial pressure should be raised to a such level that its value at the end of the excursion to the maximum authorised depth does not exceed $p_{O_2} = 48 kPa$. If the oxygen partial pressure falls below the minimum permitted value of $p_{O_2} < 44 kPa$ it is necessary to raise the oxygen partial pressure to the correct value as quickly as possible after this operation. During decompression it may be necessary to change the decompression method in cases of loss of Hx or oxygen mixture supply, occurrence of symptoms of oxygen poisoning, occurrence of changes in the ascent rate. In such cases, it is necessary to follow the emergency plan and procedures.

During the ascent in the course of a 24-hour decompression, two decompression stops should be

implemented amounting to the total of 8 hours of stop at any selected depth. The minimum time for one stop should be 2 hours. After decompression, divers remain at risk of an occurrence of decompression sickness *DCS*. For this reason it is required that they remain in the immediate vicinity of the chamber for a minimum of hours from reaching the surface. For the following 48 hours they should stay at a location that enables their transport to the chamber within a maximum of 30 minutes. Divers are not allowed to travel by air for up to 72 hours from the time decompression is completed after saturation⁵⁷.

After surfacing, no one should enter the chamber until effective ventilation has been performed⁵⁸.

The severity of the impact of a possible materialisation of the risk of habitat decompression is moderate and equal to $I = 8$ on a relative ten-point ordinal scale. Due to the possibility of operator errors resulting from incorrect record keeping, lack of control and incorrect calculations not subject to verification and consequent violation of decompression procedures, the probability was estimated at a low level and on a relative, ten-point ordinal scale was defined as $P = 5$. The level of risk detection was estimated to be possibly average, i.e. at $98\% > D\% \geq 99.7\%$, which corresponds to the relative value of $D = 6$ on a ten-point ordinal scale. The value of the relative risk number in this case is at the level of the cumulative value $RPN(SOD) = 240$, tab. 3.

In order to reduce the risk of operator error, as a countermeasure against failure to meet the recommended decompression rate, timing of decompression has been used together with an audible alarm indicator, with parallel systematic control records kept at set depth differences ΔH e.g. every $3 mH_2O$. Such a method allows comparison of the practical decompression schedule with the theoretical one included in the decompression schedule. This allows the identification of possible discrepancies such as e.g. decompression delays or acceleration. It must be remembered that in the case of a delay, decompression cannot be accelerated to compensate for the rate difference. In the event of loss of heliox or oxygen supply, alternative plans of action are provided and included in the dive technology. No changes must be made to decompression schedules without the knowledge of the saturation manager and physician.

This results in a reduction in the relative probability of the risk materialisation, to an unlikely level, estimated at a relative level of $P = 4$, and an increase in the probability of detection to full, due to the expected alarm signalling of an exceedance of a control parameter, along with early notification of a likely exceedance of the tolerance limits: $D = 4$. This allows the risk number to be reduced to $RPN = 128$, lying below the critical value.

The risk at this level as residual should be accepted and continuously monitored through intensified controls, continuous and successive measures leading to a reduction of the risk through the possible implementation e.g. of additional safety devices. The product $SO(RP) = SD(RN) = 32$ obtained following hazard compensation demonstrates, inter alia, the non-ideal detectability of the defects that are most dangerous to divers' safety. Normally, using only the limit values of RPN to determine the need to implement preventive measures is unacceptable and, as mentioned earlier, is not a recommended practice. Priority should always be given

to high values of S^{59} making sure that the risks have been compensated for. The implemented actions have resulted in a reduction of the probability of the risk materialising and its consequences to an unacceptable level $RPN \geq 100$. However, with the current level of technological capabilities, the level achieved is the lowest possible and justified. Monitoring requires planning additional ways of responding to the risks, which should be included in the *SOP in the so-called OCAP plan*⁶⁰. The control plan is the developed and approved decompression schedule, in the case of discrepancies the potential countermeasures for the operator must be known, described and implemented.

RE. 13 EVACUATION FROM THE HYPERBARIC COMPLEX

Undertaking an evacuation from the hyperbaric complex may be a necessity in critical cases related e.g. to the inability to control a fire in the simulator hall of *DGKN – 120* or in the habitat. In the case of sudden disasters⁶¹ any form of hyperbaric evacuation is questionable and may not be effective.

Hyperbaric evacuation should only be considered as a last resort and only when the saturation dive supervisor is confident that it will be of greater benefit than leaving the divers under pressure in the habitat. When the exposure is conducted at *DGKN – 120* due to the nature⁶² of exposure resulting in a reduction of many critical hazards the decision to evacuate seems unlikely but possible. Even in an emergency situation during operational dives, hyperbaric evacuation is rarely used.

It should be noted that there is no one-size-fits-all method of evacuating divers from a habitat that is suitable for every eventuality.

A hyperbaric evacuation system *HES* is required for all operational saturation dives⁶³ provided that, in the event of evacuation from a vessel or other hyperbaric installation, it is possible to evacuate all of the divers from the habitat to a designated location where the divers have the possibility to continue decompression in a safe manner. The hyperbaric evacuation system should encompass planning, procedures, actual means of evacuation, emergency centre, contingency plans, etc. Usually *HES* includes evacuation equipment in the form of a hyperbaric rescue unit *HRU*⁶⁴ such as a hyperbaric lifeboat *SPHL*⁶⁵ or an evacuation hyperbaric rescue chamber *HRC*⁶⁶. In the case of the *DGKN – 120* simulator located on land, the only way to evacuate is to move divers from a pressurised habitation chamber *Dzwońiec* to a separated chamber *Przejściówka* or *Kobuz*. This may not be sufficient or safe for divers in every possible scenario. In extreme situations like a spreading fire, evacuation of divers under pressure may not be feasible. The complex cannot be connected to an *HRC* or a diving bell⁶⁷, which could be a reliable alternative. *HRU* should be capable of keeping divers under proper pressure with life support for a minimum of 72 hours⁶⁸. According to the requirements of *DNV, IMCA* [25,26] the maximum transfer time for divers to *HRU* is $\tau = 15$ minutes. The next phase of the evacuation is moving the *HRU* so that it is at a minimum distance of 100 m from the site of the complex e.g. for *DGKN – 120* it is the maximum of $\tau = 30$ minutes⁶⁹. The time required to transport *HRU* to a safe location should be as short as possible and planning should be based on completing the transfer in a time equivalent to $\leq 75\%$ of the planned *HRC* protection time.

In the absence of the above-mentioned possibility of evacuation from *DGKN – 120* it may be

unsustainable to make an authorised excursion to a maximum depth less than the saturation plateau⁷⁰. In practice, the tables limit the depth of excursions made and thus the dive range. They do not require decompression to be undertaken when returning to plateau saturation, while maintaining a certain speed, which is limited. In cases of emergency and where it is not possible to evacuate the habitat under pressure, the diver can be evacuated by ascending to a lower depth within the limits of the permitted excursion. If necessary, the diver should be brought to the surface and immediately transported to a suitably prepared safe therapeutic hyperbaric chamber e.g. *RLKZH*. Once in the chamber, compression with heliox should be performed to the saturation plateau. Treatment of diving sickness symptoms during saturation is different than following decompression after saturation dives and dives outside the saturation zone [23]. During saturation, the diver should be recompressed from the saturation plateau with a graduation in increments of $1.5 \text{ mH}_2\text{O}$ (5 fwc) at a rate of $1.5 \text{ mH}_2\text{O} \cdot \text{min}^{-1}$ (5 fwc $\cdot \text{min}^{-1}$) until a depth of relief is achieved. Recompression to a depth greater than $9 \text{ mH}_2\text{O}$ from the onset of pain symptoms is not usually required. Once the depth of relief has been reached, a therapeutic mixture should be supplied to the diver to breathe through the BIBS systems. The therapeutic mixture can be *Hx*, for which the oxygen partial pressure is in the range $p_{O_2} \in [150; 280] \text{ kPa}$. Breathing the therapeutic *Hx* mixture should be interrupted every 25 minutes for 5 minutes of breathing of the atmosphere of the complex. Depth treatment should continue until symptoms subside, but no less than for 2 hours.

Another solution that may be more appropriate in this situation is conscious treatment of symptoms, as in procedures used after bringing a diver to the surface without decompression, or in the case of illness that manifests itself during rest after decompression from saturation, which is carried out in accordance with the typical principles of treating diving illnesses using air or air-oxygen methods. Due to the change in the breathing mixture from heliox to air and/or oxygen, attention should then be paid to the risk of counterdiffusion and oxygen toxicity in the pulmonary and neurological forms of *CNSyn* [19]. Typically, treatments in the saturation zone can also be applied as a final treatment of *DCS* after dives outside the saturation zone, as in the system developed by *Comex*.

By default, the treatment tables *TT 12₈₆ Cx*, *TT 1886 Cx* and *TT 3086 Cx* provide a treatment recompression regime for *Type I DCS* symptoms occurring after air or *Hx* dives. If after $\tau = 15$ minutes from recompression to $12 \text{ mH}_2\text{O}$ the symptoms of *DCS* have resolved then treatment is according to *TT 12₈₆ Cx*. Otherwise, treatment is continued according to *TT 1886 Cx*. Symptoms of *Type II DCS* are treated according to *TT 3086 Cx*.

If *DCS* occurs during air or heliox saturation outside the saturation zone, *TT B₈₆ Cx* may be used for *Type I DCS* symptoms when the *DCS* symptoms subside within 15 minutes, if not it is required to use *TT SB₈₆ Cx*. If the diver's condition worsens during treatment, it is necessary to move to a special saturation table *TT N₈₆ Cx*. The saturation table *TT N₈₆ Cx* is also used to treat symptoms of *Type II DCS* after air or *Hx* saturation, or operational *Hx* dives outside the saturation zone [27].

The efficacy of such methods should be highest, but their duration is long, hence, as mentioned, it is more effective to implement treatment using treatment tables, the most popular of which is the *US Navy* system adopted in the Polish Armed Forces [6,19]⁷¹.

During saturation *Type I DCS* may occur after an excursion to depths less than saturation *plateau* or during decompression after saturation completion. In all cases, the history of the onset of pain symptoms and their severity should be carefully investigated. *Type I DCS* arising during an excursion from the saturation plateau and up to 60 *minutes* after an excursion above the saturation plateau depth should be treated as *Type II DCS*, as most often symptoms of *Type I DCS* are only a harbinger of more serious complications [27].

The severity of the impact of the possible materialisation of the risk associated with the evacuation of the habitat is high, i.e. $I = 8$ on a relative, ten-point ordinal scale. Due to the lack of a means of effective evacuation and the inadequacy of *DGKN-120* to transfer pressurised divers to the *HRC*⁷² in an extreme situation, the options described above for the safe evacuation of divers outside the complex from medium or high saturation depths are limited and inevitably involve the need for immediate diver treatment. This reveals the need for additional dive protection in the form of a stand-alone hyperbaric chamber *RLKZH*. The omission of decompression on both short duration and saturation dives in adverse conditions in the absence of adequate safety and treatment procedures may result in fatal consequences. The *KTPP AMW* saturation complex is currently the only operational habitat for treatment under saturation conditions and for conducting training long duration dives at⁷³ in the Polish Armed Forces without the possibility of continuing saturation treatment at a higher reference centre.

The technical, organisational and logistical barrier revealed affects the likelihood of the risk materialising, which is offset by the extremely rare cases of the actual need to evacuate divers from saturation, particularly in simulated dives conducted on land. It was estimated at a small level and, on a relative order scale of ten, was determined to amount to $P = 3$. The level of risk detection was estimated to be as average, i.e. at $98\% > D\% \geq 99.7\%$, which corresponds to the relative value of $D = 6$ on a ten-point ordinal scale. The relative value of the risk number in this case is at the level of the cumulative value $RPN(SOD) = 144$, tab. 3.

The risk must be actively accepted and monitored due to the lack of transfer possibility to *HRC* from *DGKN-120*. Active risk acceptance includes the provision of a contingency plan in the form of treatment procedures and technical reserves⁷⁴ in the event of an emergency. In addition, the likelihood of evacuation of divers should be minimised through proactive prevention measures by eliminating other risks impacting this⁷⁵. At the same time, measures should be taken to obtain an independent treatment chamber for the duration of saturation in the event of unforeseen circumstances. In other cases not requiring evacuation, the concept of securing and treating divers in habitat was arbitrarily adopted.

This reduces the relative probability of the risk of a hazard materialising to an unlikely level, estimated at the relative level $P = 2$, and maintains the probability of average detection of $D = 4$. This allows to reduce the risk number to a value $RPN = 96 < 100$ lying below the

critical value.

The risk at this level as residual should be accepted and monitored. It is important to be aware that despite this fact, the intensity of the risk posed is still high and must not be ignored.

The relative risk number $RPN(SOD)$ in the *FMEA* risk analysis before and after the introduction of corrective measures and compensation for the materialisation of risks is shown in Fig. 3 and 4.

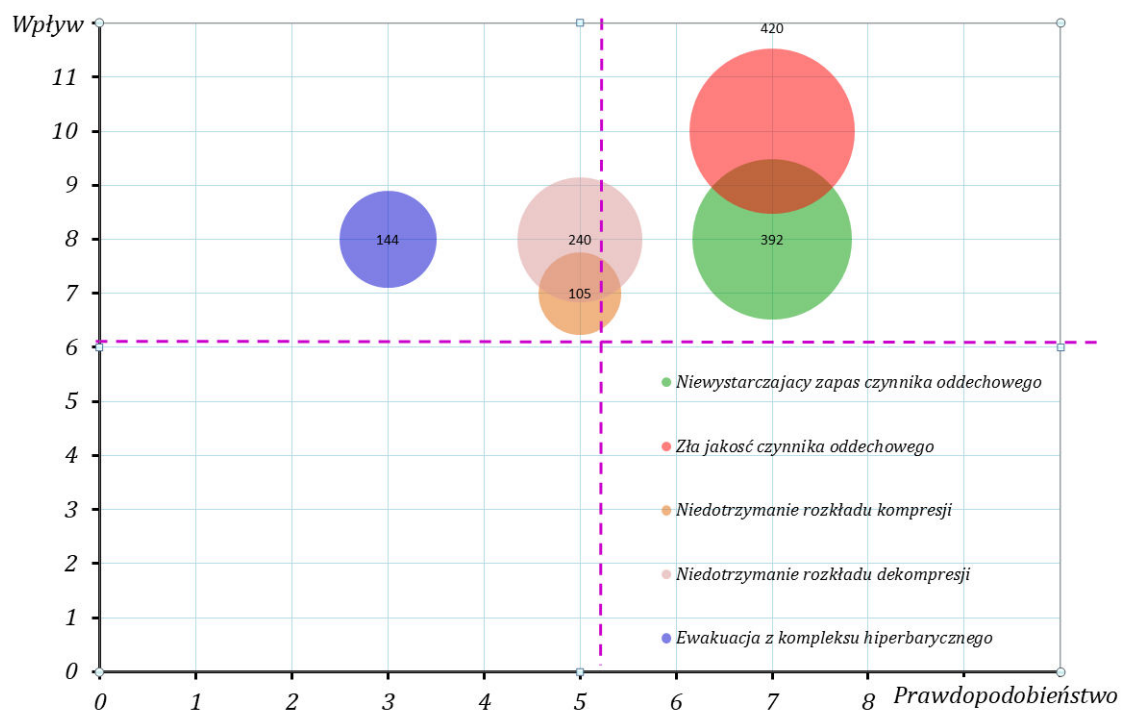
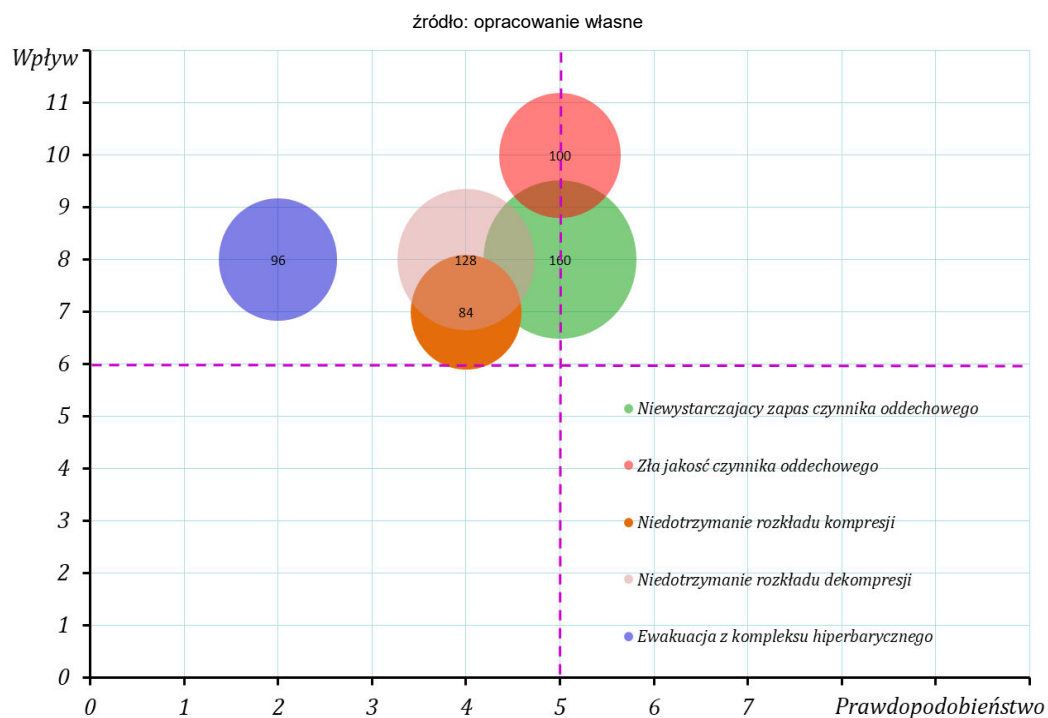


Fig. 3 Relative risk number RPN (SO) in the $FMEA$ risk analysis before the introduction of corrective actions and compensation of hazards materialisation from tab. 3. Source: own study.



CONCLUSION

As mentioned earlier, the pressure exposure process is only one element of the diving operation scenario, thus its safe implementation affects the effectiveness of the dives. As mentioned earlier, the pressure exposure process is only one element of the diving operation scenario, thus its safe implementation affects the effectiveness of the dives. The analysis of hazards, development and verification of certain anticipated and feasible scenarios as a response to identified risks is highly relevant when seeking a rational approach to diving, taking into account the logistical and economic context. Reducing any risk to an acceptable level as a result of the adopted risk response should not result in a lack of monitoring, but only in the establishment of an appropriate hierarchy for reviewing the diagnosed risks. The possible cumulative effects of hazards from different sources on the analysed hyperbaric exposure process should always be taken into account. Classifying, prioritising and quantifying risk sources, together with a description of how to respond to the diagnosed types of risk, is convenient for further exploration in an approach using the FMEA matrix.

The analysis carried out focuses on the diagnosed key possible technical risks, which are intrinsically linked to the diving technology used and its

interaction with the diving environment and the diving complex in the process of a hyperbaric exposure.

Based on the conclusions of the *risk* analysis, actions should be taken to improve the current *SOP* procedures, instructions and technologies, as well as the process of obtaining funding for the necessary investments including reserve plans that can be used to compensate for inherent *risks*. Many of the measures taken have already had the desired effect and have resulted in the establishment of redundant safeguards for the diving process such as the multi-level capability for physical and chemical analysis. Not all the procedures for responding to the identified *risks* were verifiable and validated as part of the ongoing project task, and are therefore being further explored in the work of the established *FMEA* team. The work in line with the risk analysis approach should continue and the process should be successively reviewed. Monitoring requires the planning of additional risk responses, which should be included in the *SOP* and *OCAP* risk response plans. All risk analysis inputs to the project should be collected, analysed and described, and conclusions should be recommended for implementation after acceptance by the internal stakeholder and the project manager. The results of the analysis performed should be verified in the implementation of the planned saturation exposures.

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- ¹ Department of Underwater Works Technology of the Naval Academy
- ² Experimental Deep-water Hyperbaric System
- ³ Failure Mode and Effect Analysis
- ⁴ Regulation of the Minister of National Defence of 21 June 2012 on the safety of underwater works in organisational units subordinate to or supervised by the Minister of National Defence (Journal of Laws No. 1, item 810, as amended)
- ⁵ or larger, if it results from the depth of saturation plateau
- ⁶ in *DGKN* – 120 the role of the diving bell for the duration of the excursion is fulfilled by a transition chamber (transfer chamber)
- ⁷ for compression and/or for ventilation of the complex in case of atmospheric pollution or fire
- ⁸ *IMCA D022* The Diving Supervisor's Manual, 1st edition, May 2000, ISBN: 1-903513-00-6
- ⁹ consumption of oxygen from the habitat atmosphere
- ¹⁰ diving bell gas was not included as the simulator is not equipped with it
- ¹¹ quads
- ¹² NATO - North Atlantic Treaty Organization
- ¹³ §11.5 and §11.6 Chapter 3
- ¹⁴ *SOP* - standard of procedures
- ¹⁵ as *poka* – yoke
- ¹⁶ e.g. SCADA - Supervisory Control and Data Acquisition
- ¹⁷ e.g. capable of measuring: CO_2 , CO , VOC , H_2O , O_2 etc. depending on product specification requirements
- ¹⁸ actuators.
- ¹⁹ ang. *SPC* - Statistical Process Control
- ²⁰ i.e. periodic inspection by an operator based on generally available simple measurement systems
- ²¹ ang. CTQ - Critical to Quality
- ²² High Pressure Nervous Syndrome High Pressure Nervous Syndrome
- ²³ irritation at low concentrations, difficult breathing, headache and, at high concentrations, loss of consciousness and death
- ²⁴ nausea and lung infections
- ²⁵ e.g. Laboratory of the Marine Technology Workshop in Gdynia of the 1st Regional Logistics Base in Wałcz (WTM in Gdynia 1RBLog) or other entities authorised to perform tests for the Polish Armed Forces
- ²⁶ meeting, in relation to the required measurement, the quality characteristics for measurement systems in terms of: resolution, uncertainty, accuracy, repeatability, reproducibility, stability and linearity
- ²⁷ an operation which, under specified conditions, in the first step establishes the relationship between the values of quantities represented by the measurement standard, together with their measurement uncertainties, and the corresponding indications, alongside their uncertainty, and in the second step uses this information to establish relationships that allow the measurement result to be obtained from the indication.
- ²⁸ working standard - a measurement standard that is used continuously for calibration or verification (checking) of measuring instruments or measuring systems. Working standards should be subjected to metrological control in accredited Military Metrology Laboratories and calibration laboratories operating on the basis of the current edition of the international standard PN-EN IEC 17025 or where appropriate, at NMIs (National Metrology Institutes)
- ²⁹ a conventionally true value
- ³⁰ reference measurement standard - a measurement standard that is intended to be used for the calibration of other measurement standards of a particular kind in a given organisation or location
- ³¹ based on an approved reference measurement standard calibrated at NMI or accredited calibration laboratories or authorised by the WCM
- ³² the best available on the market
- ³³ verification of measuring instruments - a set of activities performed by accredited WOM and other laboratories to determine the technical and metrological characteristics of a measuring instrument and to state on this basis and certify the conformity of these characteristics with the relevant requirement specification
- ³⁴ the capability of a measurement system determines its functional correctness and the fulfilment of its quality characteristics
- ³⁵ e.g. accreditation by the Military Metrology Centre (WCM) and/or the Polish Centre for Accreditation (PCA)
- ³⁶ not compliant with the requirements of the Polish Armed Forces and NATO and the MSA approach to qualification of measurement systems for process surveillance
- ³⁷ the implementation of automated systems is therefore sought so as to exclude operator variability
- ³⁸ the components of accuracy and correctness in relation to the tolerances of the supervised process are determined according to the MSA approach
- ³⁹ *IMCA D022*
- ⁴⁰ Breathing Air Purification Control System
- ⁴¹ independent measurement of oxygen, carbon dioxide, carbon monoxide and helium for habitat compartments
- ⁴² *HPNS* - High-Pressure Nervous Syndrome
- ⁴³ *CNS* - Central Nervous System
- ⁴⁴ care should be taken not to create a hypoxic atmosphere of $p_{O_2} < 21 \text{ kPa}$ during the entire compression process
- ⁴⁵ recommended within the limits of $0 - 60 \text{ m H}_2\text{O}$
- ⁴⁶ e.g. when key systems fail (e.g. measuring system), when an accident occurs (e.g. bone fractures), etc.
- ⁴⁷ for deep dives it is also necessary to define the maximum possible time of stay at the maximum depth due to the hazard of an occurrence of *CNSyn*, but with emergency decompression termination during saturation dives such risk does not exist
- ⁴⁸ due to oxygen toxicity
- ⁴⁹ a 24-hour leak test
- ⁵⁰ $RPN(SOD) = Sev \cdot Occ \cdot Det$
- ⁵¹ recommended improvement action based on concrete conclusions: results of research/ tests/ experiments/ analyses/ costs/ variant/ knowledge/ standardisation/ procedures
- ⁵² according to AIAG
- ⁵³ occurrence
- ⁵⁴ detection
- ⁵⁵ For example, if decompression is to be carried out at $\dot{v} = 1.5 \text{ mH}_2\text{O} \cdot \text{min}^{-1}$, then the depth can be varied by $0.3 \text{ mH}_2\text{O}$ every 12 minutes
- ⁵⁶ in order to prevent an excessive drop in oxygen partial pressure during the excursion
- ⁵⁷ in some diving technologies it is recommended that divers stay close to the chamber for 12 hours and not to fly above 600m for 24 hours. Flights below 600m are allowed after 14 hours
- ⁵⁸ e.g. risk of hypoxia
- ⁵⁹ severity
- ⁶⁰ Out of Control Plan
- ⁶¹ in open water diving, such accidents may include the sudden sinking of a vessel, a major explosion, fire or adverse weather conditions
- ⁶² in a shore-based simulator
- ⁶³ hyperbaric evacuation system
- ⁶⁴ hyperbaric rescue unit
- ⁶⁵ self-propeller lifeboat

⁶⁶ hyperbaric rescue chamber

⁶⁷ in principle it is unacceptable to plan the use of a diving bell as a hyperbaric rescue unit (*HRC*)

⁶⁸ IMO Guidelines and Specifications for Hyperbaric Evacuation Systems Resolution A.692

⁶⁹ the time commencing from the command to activate the HRU

⁷⁰ during a saturation dive, the diver can change depth both downwards and upwards

⁷¹ The dive safety manual at the Polish Navy should be supplemented with aspects of treating severe cases also under saturated conditions

⁷² is not included in the equipment of the *KTPP AMW*

⁷³ the facility is not kept permanently at full capacity for saturation treatment and therefore cannot be considered as an alternative treatment site

⁷⁴ autonomous hyperbaric chamber

⁷⁵ e.g. fire risk