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SELECTED RISKS OF THE DECOMPRESSION PROCESS, PART II: ANALYSIS OF SELECTED TYPES OF RISK

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ABSTRACT

The safe transition from a higher pressure atmosphere to a lower pressure atmosphere is accomplished by planning the decompression process, typically through changes in pressure and/or composition of the breathing mix in a function of time. However, the decompression process is affected by a much greater number of inherent factors than changes in pressure and composition of the breathing mix. Their values should be kept within certain ranges, however, there are circumstances when it is not possible to maintain control over them. In this situation, they become elements of the residual risk of the decompression process. The safety of decompression should be ensured, inter alia, by analysing the residual risk for each execution of the decompression process.

Keywords: decompression, risk, hazard, decompression sickness.

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INTRODUCTION

The inherent risk analysis presented in this paper assumes compliance with all regulatory requirements and principles of good diving practice, such as adaptive training, hygiene maintenance, and preventive health measures, leading to the continued ability to safely undergo decompression [1].

R[1] (X) is a function of a random variable X expressing the probability of an uncertain potential event $x \leftarrow X$ or a combination of events $x_1..x_n \leftarrow X$, which, in the case of exposure to them in time τ may materialise and have an effect on target accomplishment in the form of a *threat* or *opportunity*. $Threat$ or $opportunity$, denoted here collectively as H[2] is the probability of realisation of a random variable X, in the form $x_1..x_n \leftarrow X$, during exposure to risk R running over a specified time segment τ: $H = \int R(X)\, d\tau$. In survival analysis, function H is referred to as the hazard function [2].

REACTION

There are different ways to respond to risk R, with the most common including the following [3]:

- acceptance of a back-up plan, consisting of the preparation of planned actions if risk R materialises,
- risk R minimisation in the form of its transfer[3] or sharing[4],
- reduction/isolation, consisting of active measures taken to reduce the likeli-hood of the risk R materialisation or reducing the impact if it is realised,
- avoidance/replacement [5], involving modification of some aspects in order to avoid a certain kind of risk R,
- substitution, which consists in seeking a method of minimising the risk R, should it be realised, by an opportunity[6] that can be seized or rejected, reinforcement, as a proactive form taken to increase an opportunity or en-hance its scope of action.

The most common way to safeguard against the materialisation of the inherent R risk of developing symptoms of decompression sickness (DCS) is to accommodate it with a back-up plan. The use of this strategy is possible if the decompression system has been designed with the use of contingency plans in mind, such as the possibility of accelerated decompression or the use of a surface intermittent decompression procedure, in the event that the diver's time in the water is shortened or that he/she needs to be evacuated from the aquatic environment. Marine systems are planned in a manner that makes it possible to complete equivalent decompression at deeper[7]stations. The lack of possibility to continue oxygen decompression is often compensated by decompression using an operational mix, etc. The most important element of a contingency plan is the modifiability of conservatism [4,5].

Rarely, effective contingency plans may result from adaptations of other studies and observations. A relatively effective method is to use air decompression tables for Nitrox Nx decompression planning by recalculating them according to the so-called equivalent air depth EAD[8]. Less effective is the conversion of air decompression tables dedicated for use in offshore conditions to decompression for elevated bodies of water, such as high mountain lakes [6].

A way to mitigate the risks resulting from a DCS event is to ensure transport to a hyperbaric facility available or to have in place: a hyperbaric chamber near the dive site, a normobaric oxygen inhalation facility, a properly equipped first aid kit, and relevant medical training for personnel, etc. The effects of the materialisation of the inherent risk R of delayed DCS symptoms are mitigated by transferring liability to the insurer or sharing it with the employer.

In the case of risk R of DCS symptoms, seeking to turn the threat into an opportunity is difficult though possible. For instance, solving the problem associated with the need to conduct periodic flushing of the breathing space of the diving apparatus. Thus, despite the lack of flushing, there is still sufficient oxygen-rich breathing mix in circulation.

Reducing the potential risk R is often achieved through the use of a variety of diving patents. For example, it is possible to reduce the effort needed to stay at depth during decompression by using buoyancy compensators, decompression buoys or via the use of a descent line. The effort required to move can be minimised by the use of underwater scooters, towing behind a boat etc. The use of good diving practices, principles of hygiene, rest, training, etc., also reduce the inherent risk R of decompression sickness.

Avoidance of the materialisation of the risk R of DCS symptoms most often consists of refraining from diving when the diver's psycho-physical condition is not satisfactory. However, in many instances, avoidance must be supported by a decision of the dive supervisor, as the determination of divers often leads to confabulation or downplaying of the risk R. This does not only mean forgoing diving when ill, sleep deprived or suffering from hangover symptoms, but also abandoning heavier diving tasks when there has been a break in diving or when stress symptoms are present.

Opportunities in avoiding the R risk of DCS pressure sickness arise rarely. For example, when a dive is safeguarded with significant technical support, such as a substantial oxygen supply, the use of oxygen breathing after the dive may be an interesting redundancy method[9] of protection against DCS symptoms. A proactive method of opportunity amplification in this case may be the use of preoxygenation prior to undertaking the dive[10]. Of course, the use of other technical assistance to support the diving process, such as the deployment of a diving bell, is an excellent proactive form of response to the R risks, but only if the technical systems are operational and reliable.

APPROACH

For most of the inherent risks R accompanying the decompression process, their indisputable detection is difficult to perform. Therefore, the risk analysis for diving with the SCR CRABE SCUBA has been performed using a simplified[11] FMEA method[12], proposing only a ranking of the inherent risk R of DCS symptom occurrence based on the probability of its materialisation and the intensity of its impact after its materialisation. The responses to some of the R risks diagnosed and addressed during the research process of the project are shown in Table 1 and Figure 1.

In addition to the occurrence of symptoms of DCS and central oxygen toxicity CNSyn[13], the inherent R risks considered related to:

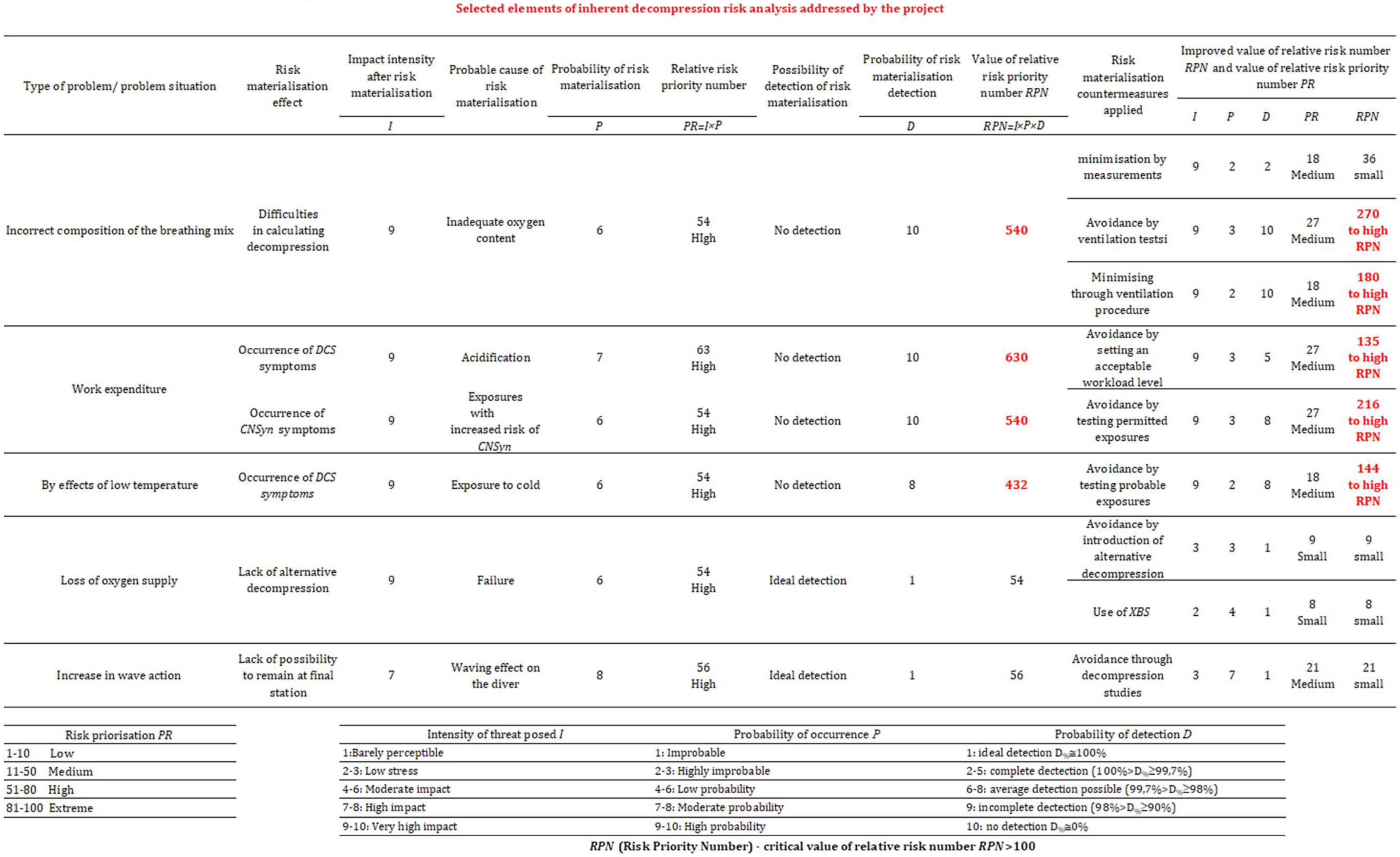
- incorrect composition of the breathing mix,
- workload,
- exposure to low temperature,
- loss of oxygen supply,
- increase in water surface roughness.

All the risks mentioned were initially given a high priority. Through the solutions proposed during the project it was possible to lower their priority to medium and in some cases to low – Table 1.

The most important problem to be solved in the project was the development of an adequate ventilation model for the diving apparatus, allowing the composition of the breathing medium inhaled by the diver to be determined [7,8]. This is always a fundamental issue when testing semi-closed circuit diving apparatuses. Without the knowledge of the exact and precise composition of the breathing mix breathed by the diver, it is impossible to estimate an adequate decompression. It usually seems that the only solution is to carry out reliable measurements for at least partial pressure of oxygen. Research on such measurements has been carried out continuously since the 1960s. However, the findings are still inadequate in an overwhelming number of situations. In addition, measurements absorb the attention of the diver, who has to concentrate on other, more relevant tasks[14].

Tab. 1

Selected elements of inherent decompression risk analysis dealt with in the project.



Selected elements of inherent decompression risk analysis addressed by the project

Type of problem/ problem situation	Risk materialisation effect	Impact intensity after risk materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Relative risk priority number	Possibility of detection of risk materialisation	Probability of risk materialisation detection	Value of relative risk priority number *RPN*	Risk materialisation countermeasures applied	Improved value of relative risk number *RPN* and value of relative risk priority number *PR*				
		I		*P*	*PR=I×P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*PR*	*RPN*
Incorrect composition of the breathing mix	Difficulties in calculating decompression	9	Inadequate oxygen content	6	54 High	No detection	10	**540**	minimisation by measurements	9	2	2	18 Medium	36 small
									Avoidance by ventilation testsi	9	3	10	27 Medium	**270 to high RPN**
									Minimising through ventilation procedure	9	2	10	18 Medium	**180 to high RPN**
Work expenditure	Occurrence of *DCS* symptoms	9	Acidification	7	63 High	No detection	10	**630**	Avoidance by setting an acceptable workload level	9	3	5	27 Medium	**135 to high RPN**
	Occurrence of *CNSyn* symptoms	9	Exposures with increased risk of *CNSyn*	6	54 High	No detection	10	**540**	Avoidance by testing permitted exposures	9	3	8	27 Medium	**216 to high RPN**
By effects of low temperature	Occurrence of *DCS symptoms*	9	Exposure to cold	6	54 High	No detection	8	**432**	Avoidance by testing probable exposures	9	2	8	18 Medium	**144 to high RPN**
Loss of oxygen supply	Lack of alternative decompression	9	Failure	6	54 High	Ideal detection	1	54	Avoidance by introduction of alternative decompression	3	3	1	9 Small	9 small
									Use of *XBS*	2	4	1	8 Small	8 small
Increase in wave action	Lack of possibility to remain at final station	7	Waving effect on the diver	8	56 High	Ideal detection	1	56	Avoidance through decompression studies	3	7	1	21 Medium	21 small

Risk priorisation *PR*	
1-10	Low
11-50	Medium
51-80	High
81-100	Extreme

Intensity of threat posed *I*	Probability of occurrence *P*	Probability of detection *D*
1:Barely perceptible	1: Improbable	1: ideal detection $D_{\%}\cong100\%$
2-3: Low stress	2-3: Highly improbable	2-5: complete dectection ($100\%>D_{\%}\geq99,7\%$)
4-6: Moderate impact	4-6: Low probability	6-8: average detection possible ($99,7\%>D_{\%}\geq98\%$)
7-8: High impact	7-8: Moderate probability	9: incomplete dectection ($98\%>D_{\%}\geq90\%$)
9-10: Very high impact	9-10: High probability	10: no detection $D_{\%}\cong0\%$

RPN (Risk Priority Number) - critical value of relative risk number _RPN_>100

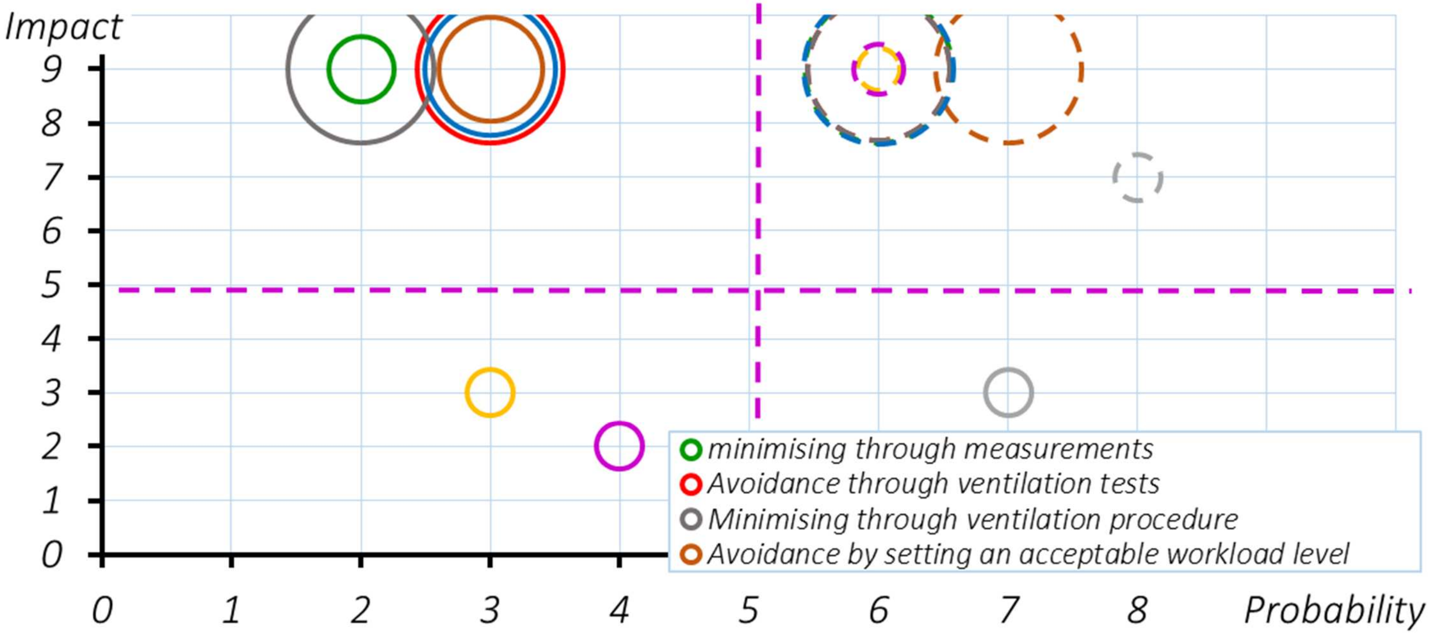


Fig. 1 Selected elements of the inherent decompression risk analysis addressed by the project: The dashed lines indicate the assessment of selected elements of inherent decompression risk assumed for elaboration in the project; solid lines show the assessment of the same elements of inherent decompression risk after their elaboration in the project.

An attempt was therefore made to carry out a thorough study of the ventilation model [8]. This enabled the abandonment of the need to ventilate the apparatus on the bottom, especially during dives using Trimix Tx, as was previously proposed [5]. Ventilation of the apparatus in the vicinity of a smart mine is not advisable, as it causes noise, which may be a signal for the detection and countermeasure systems installed in the mine. Besides, the process of periodical ventilation costs time, time which should be maximally used by the diver engaged in useful work, without the need for unnecessary concentration on operating the diving equipment. The development of an adequate ventilation model within the project reduced the risk R priority associated with the unknown composition of the respiratory agent to medium [8].

During the study, divers were encouraged to exert effort by stepping onto a resistance plate, simulating swimming in flippers, at an intensity that they could normally sustain for long periods of time. When the cold during the mission was too uncomfortable for the divers, they were allowed to increase their physical activity even above the level of effort they normally expended. The intensity of pressure on the plate was measured using strain gauges, allowing the results to be compared across dives by the same diver and between divers. This made it possible to establish that the effort expended in this way is compensable by the level of conservatism applied.

When investigating the possibility of an occurrence of a central form of oxygen toxicity CNSyn, divers were also required to cessate any activity. This made it possible to determine whether there was an increased risk of developing central oxygen toxicity CNSyn. As a result of the research, the risk R priority associated with work expenditure was lowered to medium. Similarly, the priority of risk R associated with divers' exposure to low water temperature was, as a result of the study, reduced to medium.

Basic decompression process requires the use of oxygen in its final phase. An original response[15] to the risk R of losing oxygen supply is the use of an external XBS source of supply[16]. The use of this solution reduces the risk R associated with a lack of oxygen supply from high to low. However, it is important to note that success is guaranteed by having the XBS system available. In low visibility waters, such as in the Baltic Sea, it can be difficult to identify a suspended element even when the system is equipped with light emitting markers. Therefore, as part of the project, the development of an Nx-equivalent decompression to oxygen decompression was adopted for the Nitrox Nx system. This allowed the risk R level to be reduced from high to low. A descent line fitted with breathing aparatus was also proposed. This would allow both oxygen and mixed gas to be administered, and the descent line tethered to the divers guarantees the availability of XBS almost throughout the diving process[17].

Outside the saturation zone, decompression is usually carried out using decompression stations, as continuous decompression is cumbersome under operational conditions, especially when carried out in deep water. Most decompression stations are evenly spaced every 3 mH_2O with the last station at a depth of 3 mH_2O. The station at a depth of 3 mH_2O is the longest. It is assumed that the dynamic effect of the waves on submerged objects extends to a depth of 5-7 times its height. Hence, a half-metre wave may have an effect on a diver remaining at the depth of station 3 mH_2O. Additionally, if the diver is undergoing decompression at the last station at 3 mH_2O with the line lowered from the ship's side, the rocking of the vessel may have an even greater effect on the diver. It may occur that one moment the diver will be almost at the surface and the next fluctuation will be at a depth significantly exceeding the depth of the decompression station at 3 mH_2O. Therefore, decompression systems dedicated to marine conditions are built in such a way that it is possible to complete the total decompression time dedicated to the last two stations at the deeper station, i.e. in the case of the system in question, at the 6 mH_2O station. Conducting a study on such a procedure provided the opportunity to reduce the high risk R associated with the increase in the region's undulation to a low level.

Some diagnosed R risks were compensated for during the project by using additional or redundant elements of the diving system in the form of additional measurements. This enabled a full FMEA analysis to be carried out in an attempt to reduce not only the priority of the risk R, but also its RPN – Table 2. This concerned:

- alcohol consumption,
- blood acidification as a result of exerting increased effort before diving,
- failure to train for decompression,
- incorrect ratio of oxygen consumption to lung ventilation,
- age.

Mandatory breathalyser testing of both working and safety divers has been introduced. The level of the estimated critical risk number RPN has been lowered to the approved level RPN=14, thus eliminating to a significant extent the possibility of allowing divers who have consumed alcohol to work.

Tab. 2

Selected elements of inherent decompression risk analysis minimised in the project avoidance.

Selected elements of inherent decompression risk analysis resolved in the project with redundant elements

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity after risk materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Value of relative risk number	Possibility of detection of risk materialisation	Probability of detection of risk materialisation	Value of relative risk priority number *RPN*	Introduced countermeasures for risk materialisation	Improved value of relative risk number *RPN* and relative risk priority number *PR*				
		I		*P*	*PR=I×P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*PR*	*RPN*
Alcohol consumption	Occurrence of *DCS symptoms*	7	Toxicological disorders	7	49 Medium	No detection	6	**294**	Avoidance through breathalyser testing	7	2	1	14 Medium	14 small
Expending increased effort prior to diving	Occurrence of DCS symptoms	9	Oxygen transport disorders through acidification	9	81 Extreme	No detection	10	**810**	Avoidance through acidification tests	9	1	1	9 Small	9 small
Lack of training in decompression process	Occurrence of DCS symptoms	8	Disturbances of decompression processes	7	56 High	Possible medium detection	8	**448**	Avoidance through hyperbaric training	8	3	4	24 Medium	96 small
Inadequate oxygen consumption to lung ventilation ratio	Insufficient oxygen content in breathing mix	9	Disturbances of decompression processes	9	81 Extreme	Possible medium detection	6	**486**	Avoidance through tests	9	3	3	27 Medium	81 small
Age	Occurrence of DCS symptoms	5	Reduced physical fitness	6	30 Medium	Ideal detection	1	30	Approval	5	6	1	30 Medium	30 small

Risk prioritisation PR	Intensity of created threat *I*	Probability of occurrence *P*	Probability of detection *D*
1-10 Small	1:Barely detectable	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
11-50 Medium	2-3: Small load	2-3: Very low probability	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
51-80 High	4-6: Moderate impact	4-6: Low probability	6-8: possible medium detection ($99.7\%>D_{\%}\geq 98\%$)
81-100 Extreme	7-8: High impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
	9-10: Very high impact	9-10: High probability	10: no detection $D_{\%}\cong 0\%$

***RPN* (Risk Priority Number) - Critical value of relative risk priority number *RPN* >100**

Similarly, mandatory testing of working divers for blood lactic acid levels was introduced. This reduced the level of the estimated critical value of the RPN risk number to the approved level of RPN=9, thus largely eliminating the possibility of allowing divers to work who had recently performed heavy work.

The project introduced mandatory hyperbaric training for divers participating in the study as both working and safety divers. This reduced the critical risk number RPN estimate to an approved RPN=96, largely eliminating the possibility of untrained divers being allowed to work.

From the very beginning, monitoring of the respiratory module constituting the ratio $\varepsilon = \frac{\dot{v}_0}{\dot{V}_E}$ of oxygen consumption $\dot{v}_0$ to lung ventilation $\dot{V}_E$ was carried out for the entire population of experimental divers [8]. On the basis of the function $\bar{\varepsilon} = f(H)$ of the averaged values $\bar{\varepsilon}$ of the ratio of oxygen consumption $\dot{v}_0$ to lung ventilation $\dot{V}_E$ depending on depth H, predictions of the module $\hat{\varepsilon} = f(H)$ as a function of depth H were made for the planned experimental decompression schedules with the assumed precision $\Delta\hat{\varepsilon}$. The results of the performed experimental dive were automatically included in a database used to determine the correlation $\bar{\varepsilon} = f(H)$ of the averaged values $\bar{\varepsilon}$ of the ratio of oxygen consumption $\dot{v}_0$ to lung ventilation $\dot{V}_E$. This approach was intended to minimise the risk R of assuming an incorrect breathing module when planning experimental decompressions. It allowed to decrease the critical RPN risk number from RPN=486 to the approved RPN=81.

The risk R associated with accepting divers who are advanced in age, with ideal detection, was at an acceptable level, as the decision to allow such a diver into the experiment could only have been made with a conscious research intention.

Some of the R risks diagnosed were only tentatively identified in the research process as suggestions for further research in the future. This concerned the possibility of using the opportunity:

- to perform a repetition dive (more than 1 h after the end of the previous dive),
- to perform a repetitive dive (less than 1 h after the end of the previous dive),
- to use surface decompression acceleration by breathing oxygen,
- to use the $40\%O_2/N_2$ mix in the depth range $H \in [0; 24]mH_2O$.

Preliminary studies on repetition dives have also been tested experimentally for Nx mixtures. With a relatively large population of these dives already at this stage, it can be concluded that these results are promising. For the repetitive dives, only pilot studies have been performed, hence it is not yet possible to draw conclusions about the effectiveness of modelling such exposures. Both types of dives are not only useful for planning repeated dives, but provide a basis for deducing the diver's required rest before the next dive.

The use of accelerated surface decompression by oxygen breathing has only been addressed theoretically.

The use of a $40\%O_2/N_2$ mixture in the depth range $H \in [0; 24]mH_2O$ is intended as an emergency procedure. This can be useful when, while remaining away from base, an emergency contingency dive has to be performed in the absence of the $60\%O_2/N_2$ breathing mix and the need to undertake dives at shallow depths. For example, to free a ship's propeller after it has become entangled in drifting nets or ropes.

ANALYSIS

The FMEA was also used to analyse the inherent risk R of decompression sickness (DCS) remaining after risk reduction, for which responses were investigated within the project. Based on expert knowledge, the analysis was performed only for selected risks accompanying the decompression process:

- carrying out hard work,
- overcooling/overheating of the diver,
- when the dive is one in a series of dives,
- the diver is untrained or has a personal predisposition to develop decompression sickness,
- the diver is obese or his/her weight exceeds 80 kg,
- the diver is over 40 years of age,
- breathing resistances,
- decompression to a pressure below atmospheric and post-dive air transport,
- local compression caused by the suit and equipment,
- forced position during work or decompression,
- flooding of suit,
- diet,
- use of food supplements and medication,
- dehydration,
- specific hazards related to the diving equipment used, auxiliary equipment, diving technology, etc.

In dives outside the saturation zone, heavy work by the diver is not allowed. In saturation diving it is possible[18] to stabilise the divers' homeostasis during rest before undertaking decompression, which is not possible in dives outside the saturation zone. With the expenditure of intensive effort, the body may switch partially to anaerobic metabolism, where one of the metabolic products is lactic acid. This results in acidification of the blood. Haemoglobin in an acidic environment considerably loses its ability to carry oxygen, thus disrupting the decompression process.

In some circumstances of the diving process it is not possible to avoid the expenditure of hard work, for example when entering a water current. The countermeasure for such a scenario, producing an impact intensity after the risk has materialised on a ten point relative scale, is estimated at the very high impact level of I=9 – Table 3. The probability of the risk materialising in the Baltic Sea on a 10-point relative scale was estimated to be low P=5, and the detection was estimated to be medium D=6, as the same intensity work is not equally dangerous for every diver. The value of the relative risk priority number was PR=45, which means the medium risk R, but the value of the relative risk number RPN exceeds more than 2.5 times its critical value $RPN_{kr.} = 100$, reaching $RPN = 270$. Avoiding hard work involves the use of tools and instruments to aid the diving process. For example, underwater scooters can be used for distance swimming, and tools can be used to carry out work. Contingency plans in the event of the materialisation of such risks involve being prepared to compensate for decompression through surface decompression accelerated by oxygen decompression or flushing with atmospheric oxygen, refraining from effort, etc.

The scenario for the emergency plan should be developed prior to the start of the dive and, if possible, reviewed with the divers and operators to ensure that everyone knows what to do once it is implemented.

Freezing of the diver is prevented by the use of passive or active thermal protection measures. When diving in cold climates, heated changing and rest areas should be provided with protection. Passive protective equipment may not always be correctly selected for the diving process and active thermal protective equipment may fail. Hence, the risk of the diver's overcooling cannot be precluded. Experiencing exposure to cold before diving or after decompression is also dangerous from the point of view of the diving process and subsequent decompression, so thermal protection of divers should also be planned during the stay on the surface before diving as well as during the rest period following decompression.

Tab. 3

Selected elements of the analysis of inherent decompression risk minimised by expert knowledge.

Selected elements of inherent decompression risk analysis resolved in the project with redundant elements

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity after risk materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Value of relative risk number	Possibility of detection of risk materialisation	Probability of detection of risk materialisation	Value of relative risk priority number *RPN*	Introduced countermeasures for risk materialisation	Improved value of relative risk number *RPN* and relative risk priority number *PR*				
		I		*P*	*PR=I×P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*PR*	*RPN*
Performing strenous work	Occurrence of *DCS symptoms*	9	Homeostasis disorders	5	45 Medium	Possible medium detection	6	**270**	Avoidance through contingency plan	9	5	6	45 Medium	**270 to high RPN**
Diver overcooling/overheating	Occurrence of DCS symptoms	7	Homeostasis disorders	4	28 Medium	Possible medium detection	7	**196**	Avoidance through contingency plan	7	4	7	28 Medium	**196 to high RPN**
Suit flooding	Occurrence of DCS symptoms	7	Overcooling	5	35 Medium	Possible full detection	3	**105**	Avoidance through contingency plan	7	4	3	28 Medium	84 Small
Diving in a cycle of dives	Occurrence of DCS symptoms	7	Homeostasis disorders	4	28 Medium	Ideal detection	1	28	Approved with contingency plan	7	4	1	28 Medium	28 Small
Lack of training or personal predisposition to develop decompression sickness	Occurrence of DCS symptoms	7	Lack of training	5	35 Medium	Possible full detection	4	**140**	Avoidance through training and increased conservatism	7	2	1	14 Medium	14 Small
Obesity or body mass exceeding 80 kg	Occurrence of DCS symptoms	7	Unsuitable fitting to breathing apparatus	4	28 Medium	Ideal detection	1	28	Approved with contingency plan	7	4	1	28 Medium	28 Small
Age above 40 years	Occurrence of DCS symptoms	5	Ageing of organism	3	15 Medium	Ideal detection	1	15	Approved with contingency plan	5	3	1	15 Medium	15 Small

Prioritisation of risk *PR*	Intensity of created threat *I*	Probability of occurrence *P*	Probability of detection *D*
1-10 Small	1:Barely detectable	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
11-50 Medium	2-3: Small load	2-3: Very low probability	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
51-80 High	4-6: Moderate effect	4-6: Low probability	6-8: possible medium detection ($99.7\%>D_{\%}\geq 98\%$)
81-100 Extreme	7-8: High impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
	9-10: Very high impact	9-10: High probability	10: no detection $D_{\%}\cong 0\%$

RPN **(Risk Priority Number) - Critical value of relative risk priority number *RPN* >100**

Tab. 3 cont.

Selected elements of the analysis of inherent decompression risk minimised by expert knowledge.

Type of problem/ problem situation	Effect of risk materialisation	Impact intensity after risk materialisation	Probable cause of risk materialisation	Probability of risk materialisation	Value of relative risk number	Possibility of detection of risk materialisation	Probability of detection of risk materialisation	Value of relative risk priority number *RPN*	Introduced countermeasures for risk materialisation	Improved value of relative risk number *RPN* and relative risk priority number *PR*				
		I		*P*	*PR=I×P*		*D*	*RPN=I×P×D*		*I*	*P*	*D*	*PR*	*RPN*
Breathing resistances	Occurrence of DCS symptoms	7	Incorrect working of apparatus	4	28 Medium	Possible medium detection	6	**168**	Checking of breathing resistances	7	4	3	28 Medium	84 Small
Air transport after diving	Occurrence of DCS symptoms	7	Homeostasis disruptions	7	49 Medium	Possible full detection	5	**245**	Oxygen inhalation	7	4	5	28 Medium	**140 to high RPN**
Local compression caused by the suit and equipment	Occurrence of skin symptoms of DCS	4	Homeostasis disruptions	4	16 Medium	Incomplete detection	9	**144**	Checks prior to diving	4	3	7	12 Medium	84 Small
Forced position during work or decompression	Occurrence of DCS symptoms	5	Homeostasis and mental state disruptions	4	20 Medium	Possible medium detection	8	**160**	Avoidance through contingency plan	5	4	8	20 Medium	**160 to high RPN**
Diet	Decompression-related load	4	Disturbances of decompression processes	3	12 Medium	Possible medium detection	7	84	Avoidance through training, medical interviews and examinations	4	2	6	8 Small	48 Small
Taking medicines	Decompression-related load	4	Disturbances of decompression processes	5	20 Medium	Possible medium detection	6	**120**	Avoidance through collecting medical history	4	4	5	16 Medium	80 Small
Dehydration / hydration	Decompression-related load	7	Disturbances of decompression processes	5	35 Medium	Possible full detection	6	**210**	Encouraging hydration during or after decompression	7	3	6	21 Medium	**126 to high RPN**

Risk prioritisation PR	Intensity of created threat *I*	Probability of occurrence *P*	Probability of detection *D*
1-10 Small	1:Barely detectable	1: Improbable	1: ideal detection $D_{\%}\cong 100\%$
11-50 Medium	2-3: Small load	2-3: Very low probability	2-5: full detection ($100\%>D_{\%}\geq 99.7\%$)
51-80 High	4-6: Moderate impact	4-6: Low probability	6-8: possible medium detection ($99.7\%>D_{\%}\geq 98\%$)
81-100 Extreme	7-8: High impact	7-8: Moderate probability	9: incomplete detection ($98\%>D_{\%}\geq 90\%$)
	9-10: Very high impact	9-10: High probability	10: no detection $D_{\%}\cong 0\%$

***RPN* (Risk Priority Number) - Critical value of relative risk priority number *RPN* >100**

Dangerous overheating of the diver can occur also both underwater and on the surface. Emergency divers, waiting on the surface for a possible rescue operation, are often exposed to overheating. Such divers must be prepared to descend rapidly underwater, and are therefore partially clothed in diving equipment. Exposing them to direct sunlight can lead not only to them overheating, but possibly to their becoming faint. Underwater, divers cannot always partially undress as they would on the surface, meaning that carrying excess cold protection can contribute to overheating later[19].

The intensity of the impact of the risk of hypothermia/hyperthermia on decompression safety following materialisation of the risk was estimated to be slightly lower than previously believed at I=7, similarly the probability of materialisation of this risk was estimated at P=4. However, the detection was assessed to be slightly worse at D=7. The value of the relative risk priority number was PR=28, indicating a medium risk R, but the value of the relative risk number RPN exceeds its critical value by about a factor of 2 and is RPN=196.

The recommended countermeasure to the materialisation of risk is to adequately manage the process of preparation for diving, diving and post-diving rest. The reaction to the diagnosed risk is therefore to avoid it and prepare a contingency plan, which is the same as for the materialisation of the risk of necessity to perform heavy work.

Diving suit flooding was singled out from the previous risk of diver's hypothermia because of the higher probability of materialisation of this risk, P=5, with a higher probability of detection of materialisation of the risk of hypothermia in the diver, D=3. Counteracting the materialisation of the risk consists in avoiding it through scheduled inspections of the suit and replacement of neck and wrist seals, also at the diver's request. The dive manager should pay attention to the tightness of the suit when verifying the diver's preparation for descent. This will reduce the estimated probability of risk materialisation to P=4, which in turn will reduce the relative risk number below the critical value RPN=84.

Successive dives, especially without completion of surface decompression, should be avoided. A required period of time should elapse since the previous dive. It is generally accepted that the effects of the previous dive will disappear after 12 hours. However, with intensive diving, for example on a daily basis, fatigue may accumulate. Fatigue may cause effects similar to heavy work, but the intensity of impact may be slightly lower and the probability of materialisation of this risk is also assessed as slightly lower than in the case of performing strenuous work. Although the value of the relative risk number ranks the priority of this risk as medium, with ideal detection the obtained value of the relative risk number RPN=28 is more than three times lower than the critical value. The reaction to risk therefore consists in adjustment to the contingency plan. The contingency plan is identical to that previously described. Lack of training or personal predisposition to develop DCS represent a high impact in the case of materialisation of the risk estimated at I=7, although the materialisation of this risk is estimated as low P=5. The estimate assumes that professional divers are aware of such risks and are unwilling to take the risk of diving without training, and if such a need exists then immediately the assumption of an increased level of conservatism for the decompression procedure is made similarly, detection at D=4 puts hope in the divers' common sense. However, in this case the relative risk number exceeds the critical value by 40%.

With knowledgeable attention to fitness through pressure and accompanying training and the application of increased levels of conservatism to the decompression procedures of stressed divers, the value of the relative risk number RPN can be brought down to a minimum level of RPN=14.

Obesity is considered a stress factor for many types of diving due to the low blood supply of adipose tissue and the relatively high potential to absorb nitrogen. This implies that once nitrogen reaches this tissue it is redistributed through cell membranes, but during evacuation there is a problem with nitrogen recovery due to the low perfusion by blood of this tissue. A strong physique associated with increased mass leads to an increased consumption of oxygen. Diving apparatus with a semi-closed circuit of the breathing mix is designed for specific ranges of oxygen consumption. If this value is inflated in relation to the design, the diver will be breathing an oxygen-depleted breathing mix in relation to that assumed in the planning of adequate decompression. Although the value of the relative risk priority number PR is similar to the previously discussed types of risk, with full detection of this risk, the value of the relative risk number RPN is more than three times lower than its critical value. Thus, the response to this risk is its approval, albeit with a contingency plan analogous to that previously discussed.

Like obesity, the issue of the age of the diver is important. The risk is not unmanageable, however, a contingency plan similar to that previously discussed is required.

Increased breathing resistances may be unnoticeable to the diver at first, but cause increasing fatigue associated with overcoming them during the diving process. Cumulative fatigue can result in shallow breathing disrupting the gas exchange and consequently lead to decompression problems. The increase in density of the breathing medium with depth undoubtedly results in an increase in breathing resistance. The CRABE SCUBA SCR is not equipped with support mechanisms which in this case could mitigate the effects of increased breathing resistance. Therefore, it is important to remember that additional workload for the diver at depths where increased breathing resistance occurs may be dangerous for the diver from the point of view of decompression.

An increase in breathing resistance can also be caused by the resistance of the scrubber, although in the SCR CRABE SCUBA this mechanism of induction of breathing resistance is less important than for other SCRs.

The intensity of the impact after materialisation of the risk of an increase in breathing resistance is high and estimated here at I=7. The probability of materialisation of the risk under the conditions of application of military procedures is low and estimated at P=4. Such a level of estimation of the intensity of impact after materialisation of the risk and the probability of materialisation of this risk gives an average value of the relative risk priority number of PR=28. Respiratory resistance detection under field conditions is difficult, therefore it was estimated here at a medium level of D=6, which gives a value of the relative risk number of RPN=168, i.e. increased by almost 70% in relation to the critical value of this number.

The response to the possibility that the risk of increased resistance to breathing may materialise is similar to that described previously, but is augmented by possibly frequent testing of resistance to breathing under laboratory conditions. Apparatus suspected of causing increased breathing resistance should be subjected to additional checks in addition to the mandatory ones. As a standard the CRABE SCUBA SCR is not equipped by the manufacturer with devices for operational checking of breathing resistance, but designing and manufacturing of such a device does not pose any problems as such devices used to be available in Polish SCRs. This approach allows to increase the probability of detection of risk materialisation to the value estimated here as full D=3, which enables to decrease the value of relative risk number to the approved level of RPN=84.

The return from the water environment does not have to be a return to the atmospheric pressure prevailing at sea level. In a saturation dive, the diver returns to the pressure prevailing at the depth of the bell and then to the saturation plateau[20]. After diving in deep caves[21] or high mountain lakes[22] the diver returns to the pressure prevailing at the water's edge.

If air transport is planned after the dive, the effect of the pressure on board the aircraft has a significant impact on decompression safety. The decompression calculated for the final pressure at sea level must in this case be accelerated or prolonged. [6]. The intensity of the impact after materialisation of this risk has been assessed as high I=7, comparable to a regular case of *bends*[23] decompression sickness[23], and the probability as moderate P=7. Since there is a possibility of full detection D=5, the product is a relative risk number value of RPN=245, which is two and a half times the critical value $\mathrm{RPN_{kr}} = 100$.

One proposed application to counteract the materialisation of this risk is inhalation of normobaric oxygen or oxygen flushing under hyperbaric conditions. This reduces the probability of the risk materialising to a relative level of P=4, corresponding to a low probability. This reduces the relative risk number to RPN=140, which is however still 40% above the critical value.

Most commonly, localised compression can cause localised obstruction of blood circulation leading to localised cutaneous *bends*. However, cases of more serious problems are known. Today, most divers use buoyancy-controlled dry suits. Failure to compensate for the prevailing pressure can lead to local skin bends, but can also cause shallow breathing, sometimes simply ignored by the diver at first. However, the cumulative fatigue caused by overcoming the breathing resistance caused by the suit will certainly become apparent after a few minutes. Sometimes the use of multiple safety factors, taken additionally by the diver, results in a lack of even gas distribution in the suit[24] causing more problems than expected benefits. The pressure of the suit can be compared to the tactics of strangler snakes, which by gradually increasing the pressure deprive their victims of life by stopping the gas exchange.

During diving, mild symptoms caused by suit compression are most common, such as unwarranted excessive exhaustion, headaches or general unwellness. However reports of diving accidents suggest that syncope may occur underwater.

It was assumed here that drastic cases will be excluded by the high awareness of professional divers, hence the intensity of impact after materialisation of risk was assumed at moderate level I=4 and probability of materialisation at low level P=4. Risk detection was originally assumed at incomplete level D=9, to raise it to medium level D=7 by addressing the dive leader's awareness of the need to check the preparedness of the diver. This results in lowering the level of relative risk number from RPN=144 to acceptable level RPN=84.

The forced working position imposes a burden on the decompression process by changing the operating parameters of the diving equipment, most importantly the diving apparatus. French experience shows that the use of Nx-SCR

CRABE SCUBA for MCM operations in shallow waters VSW may lead to the occurrence of pulmonary oedema accompanied by dyspnoea during the dive and later may lead to the appearance of fluid in the lungs or even death. This is due to the effect of negative pressure in the breathing space of the diving apparatus accompanying the expenditure of considerable effort and exposure to cold [12,13]. This may also be exacerbated by excessive hydration [14,15].

The intensity of the impact after the materialisation of the risk was assumed to be moderate, I=5, although a fatality has been diagnosed, based on the assumption of a cumulative adverse event. The probability of the risk materialising is low and has been estimated here at P=4. The detection lies on the borderline between incomplete and moderate D=8. This estimation results in a relative risk number by 60% higher than the critical RPN=160. The response to this risk should be design changes to the apparatus to reduce the possibility of negative pressure in the breathing space. In the absence of cooperation in this respect, diving operations should be planned with caution and in anticipation of possible problems.

Diet is an often overlooked risk causing decompression stress. This is unwise, although the parameters associated with the materialisation of this risk estimated here put the relative risk number at an acceptable level of RPN=84.

The diet can have an adverse long-term effect, as in the case of excessive growth of adipose tissue in a diver. However, it can also have a direct effect when taking dietary supplements, foods that cause bloating, acidification of the blood through unsuitable fluids and foods, etc. The combination of several risk factors coexisting with the risk of an inadequate diet may lead to a breakdown of the compensation mechanism of the negative factors assumed in the decompression procedure, resulting in an occurrence of DCS. Conducting periodic medical checks, a toxicological history prior to diving, constant building of physical form, etc., contributes to lowering the likelihood of this risk materialising and increasing the probability of detection. This further reduces the relative risk number to RPN=48.

The use of certain medications should eliminate the diver from a planned dive. The above mentioned use of nutritional supplements may be as burdensome as the use of medication. Sometimes it can seem that supplements or medicines of plant origin do not cause significant bodily changes. This conviction can be fatal. A feature of synthetic remedies is that they have a known, standardised dose of the active agent, whereas drugs or dietary supplements of plant origin may have an approximate dose of the active agent. However, the agents contained in plants are often extremely active, for example plant toxins. The probability of the risk materialising compared to diet is higher, estimated here at an unlikely level of P=5. When medicinal agents are taken, their coincidence with the decompression procedure must be suspected, hence the probability of detection is at the limit of complete and average detection D=6. Conducting a pre-dive interview focused on medication and supplements taken will partly reduce the likelihood of risk materialisation and slightly increase detection, reducing the relative risk number to an acceptable level of RPN=80.

Excessive hydration causes diuresis, which is troublesome during diving as it is not always possible to urinate. It is believed that excessive hydration is one of the factors facilitating the development of pulmonary oedema[25]. In turn, dehydration puts a strain on the heart[26] and reduces the efficiency of decompression[27]. Therefore, during decompression carried out in the habitat, divers are encouraged to consume water, while before diving they are advised against excessive hydration.

The intensity of the impact after materialisation of the risk of excessive hydration or dehydration is high and estimated here at I=7 on a 10 point scale. The probability of the risk materialising is estimated as low P=5, taking into account the diver's awareness of the risk. A medium detection of D=6 is possible based on the observation of urine colour[28]. Applying an appropriate hydration balance can reduce the probability of a risk materialising to a very unlikely value that is P=3, resulting in a reduction in the relative risk number RPN from a value of RPN=210 to RPN=126, which is slightly higher than the critical value RPN_{kr}=100.

CONCLUSION

The lack of effort to maintain the capacity to safely undergo decompression may render the developed decompression schedules largely inadequate. This inadequacy is associated with an increased risk of decompression sickness above the 5% limit assumed for military diving operations.

The downgrading of a risk to an acceptable level, as a result of the adopted risk responses, should not result in the absence of monitoring of that risk, but only in the prioritisation of an overview of the possible risks diagnosed. Consideration should always be given to the coincidence of different risks and their possible cumulative disruptive effect on the decompression process. The buffer of increased conservatism adopted in the development of the decompression process can be overcome not only by a single type of risk, but by the cumulative effect of several risks. It is good practice to conduct an in-depth risk analysis resulting from the adoption of a combination of risks for a particular diving operation. With some experience, it is not necessary to classify and describe the individual risks that may occur during a dive, but only how to respond to the diagnosed risks, however, with the use of FMEA tables.

The analysis performed focused only on the diagnosed major groups of possible disruptions to the decompression process. Based on the risk analysis, an attempt was made to enrich the decompression system with such back-up plans that could be employed in the event of an increase in the inherent risk of decompression sickness symptoms (DCS) and some other diving diseases (DCI)[29]. Not all the procedures for responding to the identified risks could be tested and validated within a single project, hence they remain pointers of direction for further research

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[1] *Risk,*
[2] *Hazard,*
[3] e.g. onto the insurer,
[4] e.g. with the employer,
[5] substitution,
[6] more often than not, a new opportunity may generate new threats, and each new threat may be related to a new opportunity,
[7] most often at the station $6\ mH_2O$,
[8] *Equivalent Air Depth,*
[9] redundancy with respect to what is necessary or customary; here the term refers to a back up system of protection in the event of failure of a part of the system,
[10] in this case, it is good practice to calculate whether the use of oxygen on the surface does not increase the risk of oxygen toxicity,
[11] with omission of probability of detection - this approach is in line with that proposed by NATO [9],
[12] Failure Model and Effect Analysis [10,11],
[13] the tasks associated with estimating safe decompression and toxicological problems form the basis for the development of any new decompression system,
[15] proposed by the manufacturer and the first user,
[16] *External Breathing System,*
[17] the safety diver remains at the head of the descent line at all times and only sends a working diver on a signal line to work in the vicinity of the mine-like object,
[18] rest may even be more than a day,
[19] this scenario can be prevented by selecting the appropriate diving equipment and accessories; for example, for distance diving, wetsuits can be worn which can be partially unzipped underwater, allowing the water to penetrate the diver's body,
[20] in most cases the depth of the bell is equivalent to the depth of the saturation plateau,
[21] changes in atmospheric pressure with increasing depth of caves or workings are not as important as, for example, the influence of virgin rock temperature, but it does happen that the diver ends up in a siphon cut off from the atmosphere where the pressure may be higher than the atmospheric pressure prevailing at that depth, or may change quite rapidly, as in caves near the sea, where its wave action or break wave has a considerable influence on the pressure prevailing in the cave,
[22] atmospheric pressure decreases with height and from a certain value it is an important parameter affecting decompression safety,
[23] only myalgia and arthralgia without development of neurological form - only DCS type I symptoms,
[24] for example, sometimes divers using buoyancy compensators with adjustable buoyancy suits also take buoyancy compensators with them, which must be tightly fitted to the suit,
[25] the pressure acting on the diver forces the body fluids out of the circuit, directing them to the internal organs, including the lungs, where they can pass osmotically into the alveolar lumen,
[26] circulating blood is denser,
[27] a large part of the gas exchange takes place in the dissolved phase, hence its deficiency causes difficulties in gas transport during decompression,
[28] preferably when the urine is slightly straw-coloured,
[29] E.g. pulmonary oedema.