

BREATHING AIR PURIFICATION FOR HYPERBARIC PURPOSES, PART II

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ABSTRACT

Determining the efficiency of breathing air purification for hyperbaric purposes with the use of filtration systems is of a crucial importance. However, when the Polish Navy took samples of breathing air from their own filtration plant for quality purposes, these were found to not meet the required standard. The identification of this problem imposed the need to undertake actions aimed at the elimination of the identified disruptions in the process of breathing air production, with the objective of assuring its proper quality. This study presents the results of the initial tests on the air supply sources utilised by the Polish Navy, which were carried out for the purpose of setting a proper direction of future works and implementing corrective measures in order to optimise the breathing air production process. The obtained test results will be used in a subsequent publication devoted to the assessment of the level of efficiency of air purification with the use of a multifaceted approach consisting in the utilisation of various types of air supply sources and different configurations of purification systems.

Key words: underwater works technology, marine engineering, diving gases.

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INTRODUCTION

The development of an issue, linked to the necessity to ensure good quality breathing mixes, resulted in the need to seek new technological solutions that would resolve the quality issues encountered during production of compressed air for breathing.

A review of the available technological solutions was conducted in order to enable selection of a recommended technical solution for the filtration system used in the tests. Depending on the obtained results this could make it possible to select a proper direction of technological modernisation of the breathing air production process with regard to the entire population of air supply sources.

Following a comparison of the operating solutions applied across the various pieces of equipment utilised, it was confirmed that the 570 design vessel equipped with EK

7.5-3 compressor along with the filtration system P140 (BAUER) meets the requirements imposed by the standard more frequently than other compressors.

Fig. 1 below illustrates the distribution of measurement points in relation to H₂O content in the breathing air in particular samples (taken quarterly) in the years 2002 - 2005.

It is noted that the EK 7.5-3 compressor exceeded the allowable threshold value related to H₂O content in cl.II breathing air only in 2 cases. Simultaneously, the comparison of results of the A3HW1 Gera compressor equipped with standard filtration system utilised thus far indicated requirement violation in 12 cases. Fig.1 indicates the upper tolerance level for allowable H₂O content in cl.I breathing air as UCL1¹ [7] (35mg/m³), and the upper threshold of H₂O content in cl.II breathing air (50mg/m³).

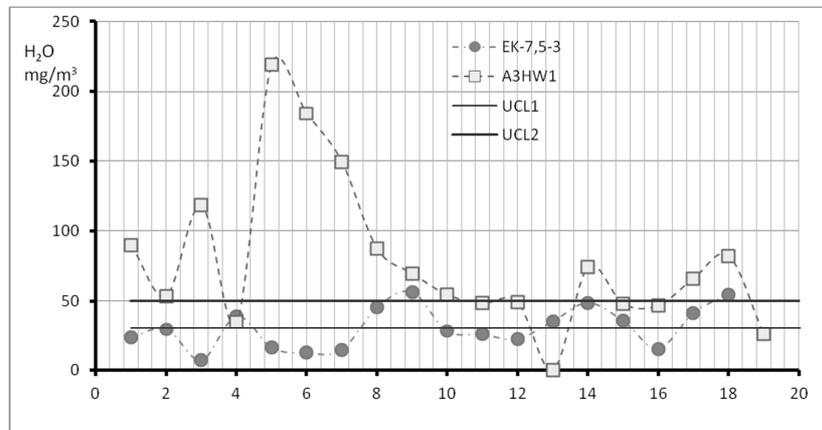


Fig. 1. Chart representing consecutive observations of H₂O content in the breathing air in various compressors in the period between 2002 – 2005.

RESEARCH OBJECT AND METHOD

In view to the above results of H₂O content measurements and the physicochemical tests carried out on the entire tested population (669 breathing air samples) in the years 2002 - 2005, it was observed that the production infrastructure (the air supply sources along with air purification systems) constitutes a critical point in the air purification process.

It should be added that each phase of breathing mix production entails a potential risk of it being contaminated. A significant element eliminating the said

risk and assuring quality is constituted by the utilised filtration system, which was identified as the research object [10].

In the analysed process, in accordance with the presented relationships (1) and (2), process performance 2 shown in fig. 2 depends on a number of enforcements on independent input variables (control variables) marked as (X₁...X_n) represented in tab.1. The application of variables should aim towards the minimisation of the defined parameters of the function of the objective for the i-th value of the contaminant marked as (C_i²).

$$\exists_{x_1...x_n}: f(x_1...x_n) \xrightarrow{\min} \{C_{H_2O}, C_{CO}, C_{CO_2}, C_{CH_4}, C_{NO_x}\} \tag{1.5}$$

$$gdzie: \forall_{i \in \{H_2O, CO, CO_2, CH_4, NO_x\}} C_i = f(x_1...x_n) \tag{1.6}$$

In consequence, it should be noted that there is a possibility of enforcing changes in the initial values ($X_1...X_n$) and their intentional modification, resulting in the minimisation of the initial parameter (C_i).

The aim was to establish which of the adjustments (in the initial values) have the greatest impact on system response, and define system sensitivity to parameters that are beyond control. In further works, the aim was to seek ways of reaching the specified minima of the function of the objective, with consideration of the problematique related to process³ optimisation⁴, which would define those factors (changes) which prove the most significant.

On this basis a hypothesis may be made, assuming the existence of a number of intentional actions, whose application would result in the elimination of the issue related to breathing air quality.

The initial answer to the posed questions was obtained after the implementation of an experiment within the planned design (DOE)⁵, with the use of a physical model. Such an approach [10] was enforced by the necessity to introduce drastic cuts in research tasks due to financial constraints as well as the urgent needs of users.

System analysis, at the stage of designing an experiment, often makes use of cybernetic models [8] characterised by a low level of complexity and operating in a way analogous to the original.

The identification of the research object, defined as the air purification process, along with the determination of both dependent and independent variables and possible disruptions which are either within or beyond control, will enable identification of the process response after the introduction of parameter changes.

It is through the determination of the cybernetic model that the prospect of establishing the deterministic model is provided. Nonetheless it should be noted that it is not always possible, nor necessary, to determine the deterministic model, hence in certain conditions it may be possible to proceed to seek a statistical model.

A further enquiry will also be conducted in order to determine whether the assignable and total observed variations contain a deterministic element in the form of a systematic error or a real variation [8, 9].

Fig. 2 below presents a simplified deterministic model adopted in a cybernetic perspective for the Initial (1) and Expected Performance (2).

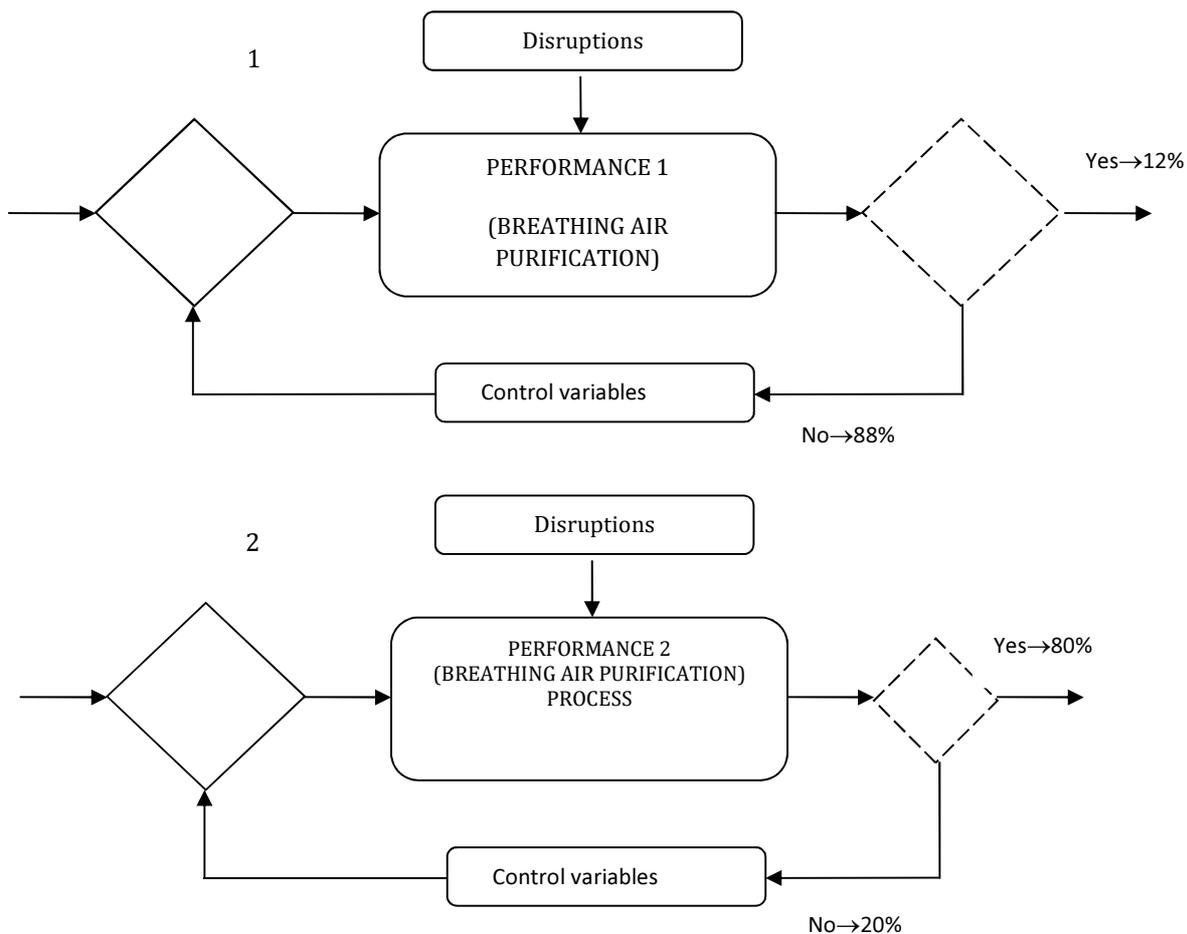


Fig. 2. Deterministic cybernetic model of the research object.

The adopted initial value was the obtained quality of the breathing air, measured with chemical instrumental analysis methods (chemical analysis⁶), with regard to estimating particular harmful admixtures (H₂O, CH₄, CO₂, CO, NO₂ and NO.) in the breathing air (C_i).

For the purposes of further works, an assumption was made that an improvement in terms of meeting the quality requirements by the entire tested population would be deemed satisfactory if the percentage share of results failing to meet the requirements related to H₂O with Performance 1 reaching ca. 88% will be reduced to a value below 20% in Performance 2.

Besides guaranteeing higher process reliability, such a performance will allow obtainment of measurable

economic benefits resulting from a reduction of the number of the necessary repeated measurements (verifications) on those air supply sources that fail to meet the specified requirements.

In the case of a measurement exceeding the normative requirements, at the stage of cause identification and removal it is commonly necessary to perform 2-4 analyses verifying the quality of produced air. The critical points in the discussed process are the identified variables marked as (X₁...X₈) presented in the table below (tab.1).

Tab. 1

Identified input values.		
No.	Symbo	Input value (variable)
1	X ₁	residual oil content at power output
2	X ₂	physical-chemical properties and filter cartridge composition
3	X ₃	water-oil separator
4	X ₄	measurement accuracy of chemical composition of the breathing air
5	X ₅	contaminant content in atmospheric air
6	X ₆	sample collection methodology
7	X ₇	test cylinder preparation technology
8	X ₈	purity of hyperbaric system elements

They have an immediate effect on the quality of parameters of the function of the objective identified as C_i and constitute its control variables. Following the general PARETO principle [7] which states that approximately 20% of factors may result in 80% of effects at the initial stage, an assumption was made that a small group of causes (X₁...X₅) may lead to the majority of the expected changes causing a change in the initial parameters.

RESEARCH

Following an intuitive approach at the stage of experiment preparation, a strategy was adopted based on the selection of a proper system for modelling studies, conducted with the use of a filter cartridge filled with a medium that was suited to the removal of various types of pollutants.

In the course of planning the experiment it was crucial to obtain as much information as possible at the lowest possible cost. The research model is defined and presented in Fig. 2.

The objective of the research was to determine an approximate relationship that would reflect the reaction of our model on the alterations in input values. The aim is to find a relationship between input and output process values which will allow identification of changes having the greatest effect on its course.

The discussed relation may be only an approximation of the actually existing links. Nonetheless, its determination may be sufficient at the initial stage of works. As it was mentioned before, the scope of the conducted research was defined through the imposed financial limitations. Moreover, as the frequent occurrence of negative research results caused the rejection of 88% of air supply sources, the situation

required urgent identification of actions offering even a partial solution to the existing problem.

As previously stated, the adopted approach focused on determining several significant variables with the greatest impact on the purification process. Having no influence on residual oil content at the air supply outlet (X₁), during the initial phase of planning the experiment and establishing accurate measurements of the chemical composition of the breathing air (X₄), it was assumed that the most significant impact on the research subject should be attributed to particular physicochemical properties and the composition of the filter cartridges (X₂), as well as the types of water-oil separator used in the process (X₃).

In consequence, at the initial stage of the studies it was possible to assume that the factors (X₅...X₈) are less significant and do not have as great an impact on the research object as (X₁...X₃). However, the said assumption requires confirmation at the experiment implementation stage as well as during further research.

Needless consideration of factors (X₅...X₈) at the stage of experiment planning could generate unnecessary costs connected with the preparation and implementation of new technologies and significantly extend the time scope required to carry out an exhaustive research.

The undertaken experiment is to provide an answer to the question whether the above input values (X₂, X₃ - the input values in the experiment) have a significant impact on parameter C_i. Comparative studies should give an answer regarding the influence of the implemented changes in input parameters (application of a new type of filter cartridge and separator) on the system's response (contaminant content after the filtration system).

In consequence, the possibility to use a different type of air purification system meeting the specified

requirements was examined. With consideration of the scale of the breathing air production process (ca. 200 compressors of different construction and working parameters), ensuring the required quality with the use of a new type (family) of filtration system constituted the key issue.

For the purpose of conducting an assessment related to the elimination of pollutants from the provided air supplies (technical means), the filtration system P61 produced by BAUER was selected for the initial tests aimed at carrying out an observation of the reaction process (through the measurement of input parameters).

The selected filtration system (Fig. 3a) consisted of:

- a micro filter [5 μ m];
- water-oil separator (automatic condenser discharge);
- control system of the saturation level of filter cartridge – SECURUS;
- safety valve;
- non-return valve;
- filter casing (with cartridge);
- filter pressure regulation valve.

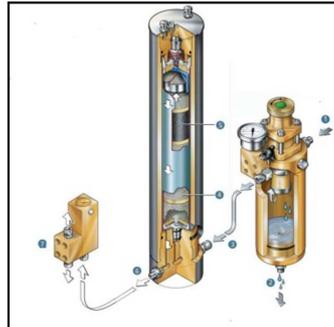


Fig. 3. Air purification filter P61 manufactured by BAUER (a); a general view of the filter installed in the air supply system of the underwater works securing base "ORTOLAN" (b), (a and b), source: (a) manufacturer's information materials, (b) own research.

Tab. 2. below presents the main technical parameters of the selected filtration system P61.

Tab. 2

P61 BAUER filter technical data (source: manufacturer's information materials).

No.	Parameter	Value	UM
1	Working pressure	225/330	[at]
2	Maximum working pressure	350	[at]
3	Yield	600	[dm ³ /min]
4	Regenerated air volume in relation to absolute pressure of 1 bar, at 20°C with the flow of 200dm ³ /min and the pressure of 200bar	1612	[m ³]
5	Working temperature range	+5 to 50	[°C]
6	Residual water content	30	[mg/m ³]
7	Residual oil vapour content	0.130	[mg/m ³]
8	Residual water content	5 (with maximum concentration at compressor inlet 25ppmv)	ppm
9	Residual CO ₂ content	400÷500	[ppmv]
10	Weight	56	[kg]
11	Dimensions	780 x 260 x 1000	[mm]

The types of standard cartridges for P61 filters are presented in the table below.

Types of the available configurations of filter cartridges (source: manufacturer's information materials).

No.	Filter type	Filter cartridge	SECURUS sensor
1	P61	MS/ MS/ MS/ MS/	-
2	P61	MS/ MS/ AC/ MS/	-
3	P61	MS/ MS/ AC / MS/	+
4	P61	MS/ MS/ AC / MS/HP/	+
5	P61	AC/AC/AC/MS/	-
6	P61	AC /MS/	+

MS- molecular sieve

AC- activated carbon

HP- hopcalite

The cartridge filling selected for the comparative tests, conducted within the discussed experiment, had the following composition of (MS/MS/AC/MS/HP).

The proposed solution was able to guarantee the most efficient removal of undesired components of the breathing air. Due to the use of a diesel engine in the tested compressors, the content of hopcalite⁷ as process catalyst was necessary for the purpose of reducing the undesired CO content.

Beside the most popular hopcalite, another available highly active oxidising catalyst is used in CO elimination based on palladium, platinum and tin.

The water-oil separator system was additionally equipped with spontaneous condensate discharge, automatically disposing of the water-oil condensate from

the filter area of the separator, produced in the course of the filtration process.

The system empties the connected devices automatically over 6 - 10[s] at an interval of 15 [min]. Another element aimed at ensuring the optimal use of the proposed filter cartridge through constant monitoring of its wear level rests in the utilisation of the SECURUS control system.

By indicating a proper visual signal, the said system informs operators on the saturation level of filter cartridges. The device offers four operational modes presented in the table below:

Tab. 4.

Performance of the monitoring system of saturation quality of the SECURUS filter cartridge (source: manufacturer's information materials).

No.	System properties and performance	Control lights
1	Regular working mode	Steady green
2	Warning of an impending cartridge saturation	Steady green + flashing yellow
3	Disconnection of the filtration system due to cartridge saturation	Flashing red
4	Disconnection of the filtration system due to cartridge absence in the filter casing	Steady red

The above system may be configured in such a way as to induce an automatic immobilisation of the compressor in the case of exceeding the allowable saturation level of the filter cartridge.

All of the enlisted devices cooperating with the filter were used for the purpose of ensuring optimal use of its filtration capacities and maximum extension of the time of its protective function, ascertaining high quality of the breathing air, low utilisation costs, and, consequently, increased process reliability.

The model system used in the study was utilised in EK2-150 compressors powered with a diesel engine in the "ORTOLAN" mobile operating base for underwater work presented in Fig. 5-7.

The "ORTOLAN" bases were produced and implemented for use in the Armed Forces of the Republic of Poland between the years 1977 - 1984, a total of 68 pcs being built. From the perspective of the needs of the

Armed Forces associated with the technical security of underwater works, the possibility of further utilising the above devices was of key significance.

Moreover, it was important to obtain results regarding the use of the chosen model for breathing air purification which would enable formulating a prognosis regarding potential elimination of results which fail to meet the requirements of the analysed population. Such a procedure would make it possible to continue to temporarily use the "ORTOLAN" bases until their planned withdrawal.



Fig. 5. Underwater works securing base "ORTOLAN".



Fig. 6. Air supply system of the underwater works securing base "ORTOLAN" – control panel.



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Fig. 7. The supply system for underwater works security base "ORTOLAN" with diving air compressors EK 2-150 manufactured by the former USSR.

RESEARCH RESULTS

Carrying out comparative tests of the model system, on the basis of the selected physical model, and following the change enforcement in X_2 - X_4 values (tab.1), allowed the obtainment of the results presented in the table below.

Tab. 5

Comparison of analyses on breathing air supply systems prior to (Performance 1) and following (Performance 2) the enforcements (X_2 - X_4). Source: own study on the basis of results of physicochemical tests performed at the CZSRMW laboratory.

No.	Mix under measurement	Performance 1		Performance 2		UM
		No. 2727 (No.1)	No. 12833 (No.2)	No. 2727 (No.1)	No. 12833 (No.2)	
1	Oxygen	20.77	20.92	20.93	21	[%]
2	Carbon dioxide	(0.0468)	(0.0317)	0.0	0.0101	[%]
3	Carbon monoxide,	0.69	0.62	0.41	0.32	[ppm]
4	Nitrogen oxides,	0.111	0.255	0.196	0.082	[mg/m ³]
5	Hydrocarbon vapours calculated into CH ₄	(3.93)	1	0.5	0.4	[mg/m ³]
6	Water vapour	(111)	(56.98)	10.95	9.55	[mg/m ³]
7	Scent	-	-	-	-	[-]
8	contaminant	-	-	-	-	[-]

Note. Brackets indicate measurement results of the breathing air samples which failed to meet the requirements.

The results of the performed laboratory measurements confirmed the effectiveness of breathing air purification via the selected system. The application of a new filter content resulted in multiple reductions of the content of particular components (harmful admixtures) in the obtained air in relation to the initial values (measured along with the original filtration system in Performance 1).

With the focus placed on those measurement results which failed to meet the specified requirements of the tested population of contaminants (see Fig.1), Fig.8-11 below present a graphic illustration of the obtained results in the comparative research with regard to the following contents: H₂O, CO₂, CH₄, CO.

Fig. 8 shows H₂O content measurements of 2 selected compressors before and after the implementation of changes. Multiple reductions in H₂O content was achieved for both supply sources from the tested sample.

The results were referred to the criteria related to the content of harmful admixtures within the scope corresponding to cl. II (C_{H2O}<50mg/m³) and cl.I requirements (C_{H2O}<35mg/m³) for breathing air (NO-07-A010). In both cases the result was below the threshold value.

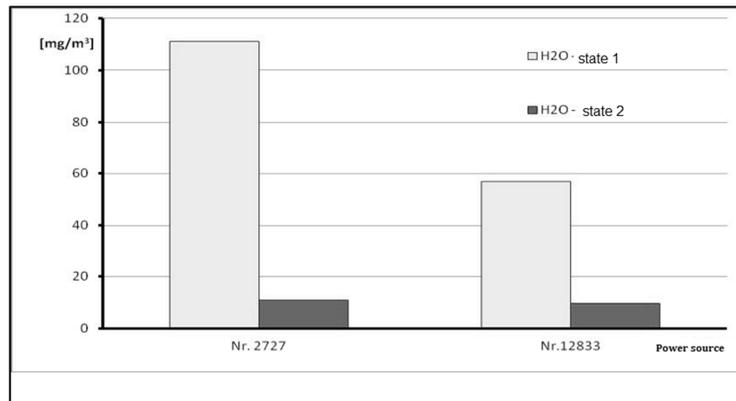


Fig. 8. Comparative research results in relation to H₂O content. Source: own study.

For comparison, below (Fig.9) we present similar results with regard to CO₂ content measurements. In both cases the results meet the requirements for cl.II (C_{CO2} ≤ 0.05%) and cl.I (C_{CO2} ≤ 0.01%) breathing air

(NO-07-A010), with one of them being within the threshold limit.

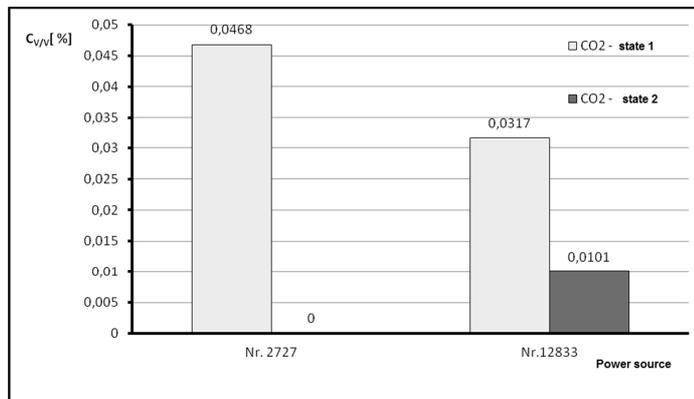


Fig. 9. Comparative research results in relation to CO₂ content. Source: own study.

Similarly to prior tests, subsequent measurement results with regard to CH₄ content confirm the efficacy of the applied solution and provide promising prognoses for a larger-scale utilisation of the proposed solution.

The results regarding CH₄ content (Fig.10) meet the requirements specified for cl.II (C_{H20} < 5ppm) and cl.I (C_{H20} < 1ppm) breathing air acc. to (NO-07-A010), in both cases they are significantly below the restricted value.

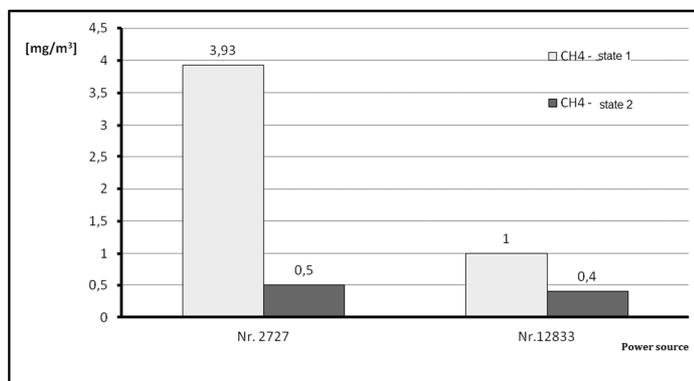


Fig. 10. Comparative research results in relation to aromatic hydrocarbons content evaluated per CH₄. Source: own study.

For comparison, below (Fig.11) we present similar results with regard to CO content measurements. In both cases the CO content meets the requirements for cl.II ($C_{CO_2} \leq 10 \text{ ppm}$) and cl.I ($C_{CO_2} \leq 3 \text{ ppm}$) breathing air (NO-07-A010).

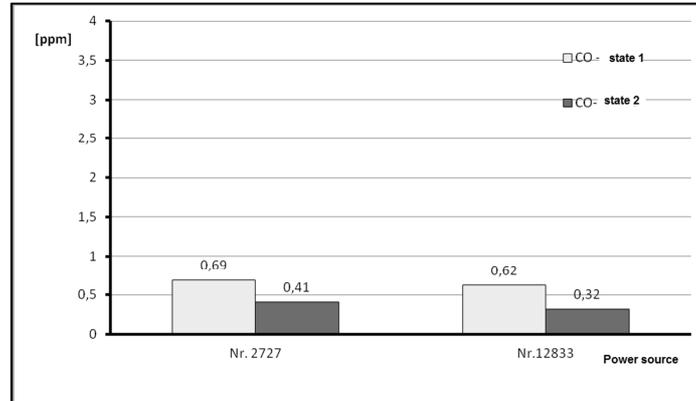


Fig. 11. Comparative research results in relation to CO content. Source: own study.

CONCLUSIONS

The promising research results following an intentional implementation of control changes provided the grounds to adopt the concept regarding their generalisation and application on a larger scale. The first stage consisted in the replacement of air supply and filtration systems in the underwater works securing bases ORTOLAN carried out between 2003 - 2004, as well as the initiation of the process of gradual upgrading of air purification systems with regard to supply sources.

For obvious reasons, a principle was adopted regarding constant monitoring of the process through accumulating measurement results in a database for the purpose of their further processing at the stage of an analysis.

By the year 2014, the database contained approximately 12,000 measurements of particular types of contaminants. This forms a representative statistical group, providing the basis to carry out further exploration of results with the use of selected scientific methods⁸ [11, 12].

As mentioned before, the implemented works allowed the observance of new phenomena at the stages of selection, elimination and classification of results that were useful in the determination of factors having an effect on the process, such as: the test sample collection (X_6), the technology of preparation of test cylinders (X_7) and hyperbaric system purity (X_8), as well as enabling a multi-criteria verification of the applied solutions.

The variables (X_6 , X_8) defined in Tab. 1 initially did not result from the presented intuitive approach nor had they been identified before the above research was commenced. They are a consequence of observations and reasoning conducted during the use of air supply sources and obtained on the basis of measurements on the tested population (database).

On the basis of observations it was possible to establish that the process was susceptible to the impact of errors occurring due to the use of improper methodology of test sample collection.

This observation made it possible to introduce

Despite the fact that the initial values (Performance 1) also met the imposed criteria it is noted that it was possible to obtain lower values in both tested cases.

corrective measures in 2006 consisting in the preparation and implementation of:

- proper methodology of sample collection for analysis;
- test cylinder preparation technology;
- preparation of elements of equipment working in aerobic conditions⁹.

Due to their significant impact on the analysed process, as well as interesting conclusions drawn at the stage of resolving the described problem, the previously defined variables will be more broadly discussed in an article to follow, describing changes occurring in the tested population upon the implementation of corrective measures at the operational stage.

The test results obtained for the system model, and the technical modernisation carried out on their basis, resulted in a gradual resolution of the defined problem. Further data analysis and filtration efficacy assessment in relation to:

- various supply sources with the use of the same filtration system family;
- the same supply sources with different filtration systems;
- the same supply sources with different drive motors;
- new types of supply sources;
- seasonality of measurement performance;
- hyperbaric system purity;
- sample collection methodology;
- operation error identification;
- technical process control possibilities;

enabled the performance of a reliable assessment of the undertaken actions and their effects, as well as formulation of a number of recommendations regarding system operation and gradual improvement in the breathing air quality. Fig.12 below presents the obtained effects in the tested population of air supply sources between the years 2002 - 2005.

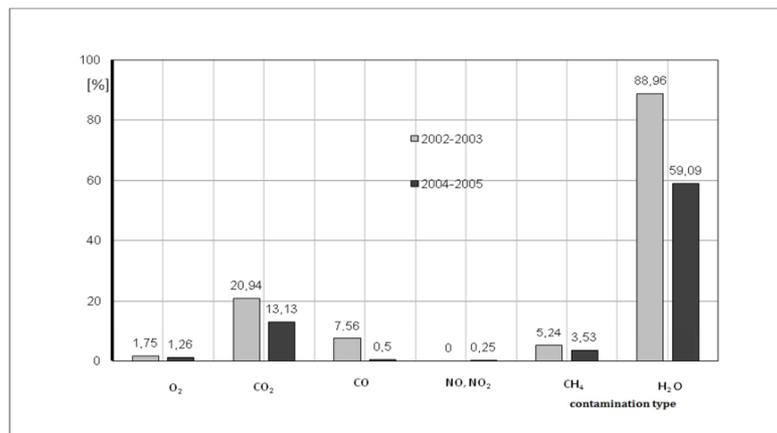


Fig. 12. The percentage share of test results on the breathing air failing to meet the quality requirements in the years 2002 – 2005.

Measurable effects consisting in the obtainment of a significant reduction in the share of negative measurements regarding particular contaminants in the years 2004 - 2005, as compared with their initial values determined in the years (2002 - 2003) provided the grounds for the continuation of works within the adopted assumption.

Undertaking targeted actions connected with the improvement of an initially unstable (unregulated) process along with the implementation of preventive measures in relation to the responsible factors with the use of various methods, techniques and tools related to

control and quality assurance will constitute an important element in further considerations.

It is also necessary to conduct further measurements for the purpose of finding an answer regarding the level of efficiency of filtration systems and the use of a multifaceted approach consisting in the utilisation of various types of air supply sources and different configurations of air purification systems.

The specified area, with particular consideration of efficiency evaluation of the applied technical solutions will be the object of the subsequent paper within the thematic cycle devoted to the quality of breathing mixes.

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¹ UCL - upper control level,

² C_i - initial parameter (measurement of the contents of particular breathing air contaminants C_{H_2O} , C_{CO} , C_{CO_2} , C_{CH_4} , C_{NO_x} in the examined sample, after the filtration system),

³ Optimisation – a method of determining the most favourable (optimal) solution (seeking a function extreme from the point of view of a determined criterion (indicator)),

⁴ Process optimisation – actions consisting in process modelling, analysis and facilitation (including production processes),

⁵ DOE – design of experiment,

⁶ Chemical analysis – qualitative (*qualitative analysis*) and quantitative study (*quantitative analysis*) of the chemical composition of the breathing air,

⁷ Hopcalite - a trade name of the mixture of copper oxide (II), cobalt oxide(III), manganese oxide(IV) and silver oxide. Substance with the properties of a porous mass resembling activated carbon,

⁸ These include: Data Mining, statistical reasoning, statistical process control, PARETO analysis, FMEA, QFD, quality optimisation methods, etc.,

⁹ Aerobic conditions – conditions in which a system or its element is in direct contact with pure oxygen or other oxygen-enriched mixes (with oxygen content >22%).