EFFECTIVENESS EVALUATION OF SOURCES OF SUPPLY AND SYSTEMS FILTER IN PRODUCTION PROCESS OF BREATHING AIR

Arkadiusz Woźniak

Department of Underwater Works Technology, Polish Naval Academy in Gdynia, Poland

ABSTRACT

The determination of how efficiently filtration systems used for the production of breathing air used in hyperbaric environments are operating is significant both from theoretical and practical points of view. The quality of breathing air and the breathing mixes based on air is crucial with regard to divers' safety. Paradoxically, a change in regulations regarding quality requirements for breathing mixes has imposed the necessity to verify both the technical equipment and laboratory procedures used in their production and verification. The following material, which is a continuation of previous publications, presents results of the conducted research along with the evaluation of effectiveness of the filtration systems used by the Polish Navy.
key words: underwater works technology, marine engineering, diving gases.

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INTRODUCTION

The failure to supply the Military Maritime Rescue System of the Navy [1] with good quality breathing mixes has resulted in a limitation in the opportunities to conduct specialist training or to perform underwater works at SZRP[1] [2,3].

System limitations resulting from the absence of a guarantee of proper quality were caused, among other things, by the use of overexploited supply sources and insufficient configuration of the breathing air treatment system. For instance, using filters containing only one type of absorbent [2] and adsorbent[3] (e.g. activated carbon or slaked lime) without the use of automated dehydration could not ensure the expected quality [4].

RESEARCH OBJECTIVE AND METHOD

The objective of the research was the performance of impact assessments on the quality of the obtained breathing air following modifications introduced in to the air treatment system of the supply sources used at the MWRP[4]. The determination of the effect of the applied enforcements on the production process will enable the selection of technical solutions that ensure the best possible quality of breathing air.

As a result of the thus far conducted works [5], a set of input variables was identified ($X_1 \dots X_5$) as presented in tab. 2, which have an influence on the filtration system, and therefore on the research object in the analysed breathing air treatment process.

An experiment was carried out [5] aimed at obtaining information concerned with the efficiency of the selected filtration system – the P61 BAUER with filter cartridge (MS/MS/AC[5]/MS[6]/HP[7]) and an EK2-150 compressor. A change in the make up of the material used in the filtration system resulted in a significant reduction in the content of particular harmful admixtures in the obtained air as compared with the initial values [5].

The promising results obtained in model tests [15] were subject to verification on the basis of their application in various types of supply sources used by the Polish Navy. Further measurements were carried out for the purpose of obtaining a system response defining the level of efficacy of the selected filtration systems.

The research was based on a multi-variant approach consisting in the use of various types of supply sources and filtration system configurations. During the breathing air production process the physico-chemical analysis is conducted on a sample taken at the supply source outlet after the filtration system.

The sample is analysed, according to the requirements [6,7] for the oxygen (O_2) and nitrogen (N_2) content, as well as particular harmful admixtures, such as (H_2O, CH_4, CO_2, CO, NO_2 i NO). Tab. 1 below, in accordance with the previously obtained research results [4,5], presents the frequency of occurrence of negative results in the years 2002-2003.

Tab. 1.

List of reasons for rejects in the breathing air analysis in the years 2002-2003 (up to the third quarter). Source: own study.

Type of contamination	Frequency of results failing to meet the requirements in [%]
H_2O	88.96
CO_2	20.94
CO	7.56
CH_4	5.24
O_2	1.75
NO_2	0

The tests on particular supply sources were carried out with the use of the BAUER breathing air treatment systems. It was assumed that the reasons for the rejects in group A presented in tab. 2 have an impact on the outcome of the process.

Tab. 2.

The identified input values in the breathing air treatment process. Source: own study.

symbol	Input value (variable)	Group
X_1	residual oil content at supply output	A
X_2	physical-chemical properties and filter cartridge composition	
X_3	water-oil separator	
X_4	measurement accuracy of the chemical composition of the breathing air	
X_5	pollution content in atmospheric air	

It was assumed that the variables defined in group A (X_1-X_5), represented 80% of the cause of the most negative impacts on results [8]. However, without further tests it is difficult to determine the degree and scale of their positive or negative impact on the air treatment process.

Due to the large scale of occurrences of rejects (tab. 1) it was required to undertake activities aimed at the correction of an unstable (irregular) production process of the breathing air through elimination of particular reasons for such instability. Implementation of final corrections with the use of various types of tools connected with quality control and assurance was achieved through the performance of efficacy evaluation of the applied changes on the basis of the obtained laboratory measurement results.

Quality assessment of the breathing air was carried out on samples subjected to physicochemical analysis. Laboratory tests on the said samples were performed under the supervision of the Maritime Rescue Command DMW (SRMDMW) at the physicochemical laboratory of the Central Institute of Rescue Equipment MW (CZSR MW). In order to guarantee the quality, the evaluation of the measurement process [9,10,11] at the laboratory was conducted with the participation of the Department of Underwater Works Technology of the

Naval Academy (ZTPP AMW). Analysis of the measurement system of the control process constituted a key condition for the guaranteeing of a reliable assessment of the technical process control. Laboratory measurements were carried out with the use of the gas chromatography method enabling determination of the percentage composition of the breathing air in accordance with the requirements NO-07-A005.

The measurements were performed with the use of the following gas chromatograph: GC 8160 by FISONS with an FID[8] and a TCD detector and TRACE ULTRA GC by Thermo Fisher Scientific in configurations with FID and TCD and PDD[9] and TCD detectors respectively. Gas chromatography along with spectrometry belong to the most common methods of analysis of breathing air and other breathing mixes.

The measurements of contaminants was also performed with the use of NICOLET ANTARIS IGS FTIR spectrometers[10] produced by Thermo Fisher Scientific. The laboratory equipment used for testing is presented in fig.1-4 below.

Fig. 1-2 Gas chromatographs GC 8160 FISONS and TRACE Ultra GC, Thermo Fisher Scientific.

Fig. 3-4 FTIR Spectrometer NICOLET ANTARIS Thermo Scientific with zirconium oxygen analyser RAPIDOX 2100ZF.

The extension with variable X_1 (tab.2) in the group of implemented input variables in the course of the performed tests allowed the assessment of the scale of impact of the type of supply source on the air treatment process.

For the purpose of process optimisation it was decided that the tests be conducted with consideration of new generation constructions, thus far not used by the Polish Navy. This enabled selection of efficient and reliable breathing air production systems.

The results will constitute the grounds for replacement of the existing overexploited supply sources which it is not possible to modernise. Obtaining a quick and significant qualitative improvement, in the examined stock of 100-140 various supply sources, is not possible solely on the basis of modernisation of old systems. The planned activities aimed to obtain high quality breathing air and to reduce the input values C_i[11] to a level within the limits established by requirements [6,7]. Thanks to the performed tests and the establishment of a database of the conducted measurements, the possibility of carrying out a periodic analysis of the works, and, what follows, the assessment of the obtained effects upon implementation of X_1-X_5 impositions was facilitated.

The results of measurements collected in the form of a tabulated database were prepared with the use of MINI TAB Release 15 software, Statistical Software and Microsoft EXCEL.

TESTS

The decision regarding the level of investment connected with successive modernisation or replacement of supply sources was based on the results of the research performed along with the analysis of efficacy of supply sources, whose results are presented below.

The analysis covers the years 2002-2013. For the purpose of selection of the direction of modernisation works at an early stage of research, the authors referred to the results obtained in the years 2002-2005, which are partly presented in the graphs below. The graphs present the measurements obtained for H_2O content in the examined breathing air samples for various types of supply sources and filtration systems. Fig. 5 depicts the original distribution of humidity measurements for the EK2-150 compressor with no applied enforcements.

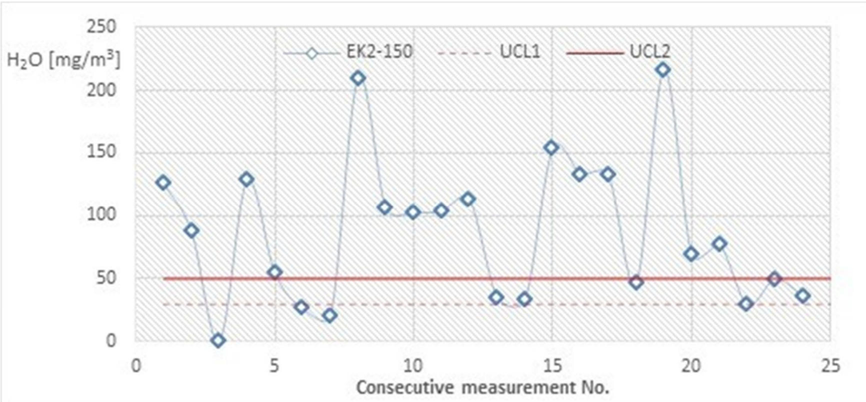

Fig. 5. Graph on consecutive measurements of H_2O content in the breathing air for the EK2-150 compressor in state 1 performed in the years 2002-2007. Source: own analysis on the basis of tests performed by physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW[12].

As can be seen, the distribution of results in the examined process is contained within very broad limits. It should be noted that the measurement results to a large extent fall beyond the defined tolerance limits and in as many as 16 cases, i.e. 66.6% of instances, they fail to meet the imposed requirements. The behaviour of the system

seems quite random and is characterised by a large dispersion, thus making process efficiency unsatisfactory from the point of view of the user. This means that the selected system elements (i.e. the filter, compressor, etc.), despite their mutual interaction, do not guarantee obtaining the minimum assumed functions of the C_i target defined for humidity as the content of $H_2O \leq 50 mg/m^3$. Hence, it was decided to concentrate on obtaining the proper position of measurement $\bar{X}$ values in relation to particular harmful admixtures (H_2O, CH_4, CO_2, CO, NO_2 and NO) in the breathing air (C_i), which should fall within the specific control limits.

Assuming that the standard deviation for the population is equal to σ, the standard deviation in the distribution of mean values is equal to $\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$ [8]. The dispersion of measurement results should not exceed the control limits located at a distance $\mp 3\sigma_{\bar{x}}$ from the defined centre line. The control limits establish the scope of the range where, according to the principle 3σ resulting from the properties of a normal distribution, 99.73% of all measurements should be contained.

For the sake of comparison of the quality of the obtained measurement results, the consecutive graphs present the results of laboratory tests carried out for systems subjected to modifications with the introduction of X_2-X_5 changes (state 2) [5] indicated in the graphs with the "M" symbol or a new generation of supply sources (X_1) along with the breathing air treatment systems. Fig.6 below presents a juxtaposition of 3 types of supply sources:

- modernised compressors EK-7.5M and A3HW1 M;
- new compressor MARINER 250E;

with regard to control limits corresponding to cl. I and cl. II of the required breathing air quality.

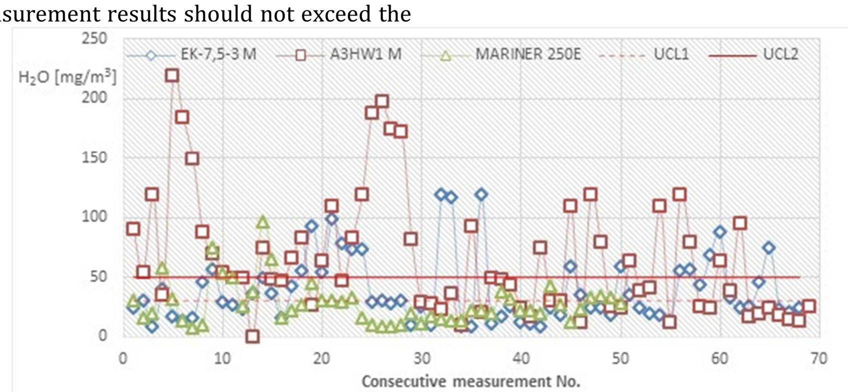

Fig. 6. Graph representing consecutive measurements of H_2O content in the breathing air for various supply sources performed in the years 2002-2013. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

It is possible to observe a significant difference in the applied technical solutions. The analysis of measurement results indicates that the most effective solution consisted in the application of X_1-X_5 enforcements (MARINER 250E). The applied enforcements X_1-X_5 (for the EK-7,5-3M compressor) are no longer as effective. The measurement results obtained for the A3HW1 M compressor depart significantly from those obtained for MARINER 250E and EK-7,5-3M compressors.

During the control of the breathing air production process each type of supply source in the examined population was analysed separately. The control was performed with statistical quality management method SPC[13] implemented with the use of control sheets. Control charts were used to monitor process quality through the control of location and variability of measurement results in relation to the defined tolerance limits.

Below we present the obtained measurement results provided in control chart IX-MR[14] in relation to the breathing air treatment process for particular supply sources. Fig. 7 & 8 present the distribution of measurement data on a control chart for the following types of supply sources: EK-7,5-3 M and A3HW1 M.

The use of statistical process control methods [12,13] in the breathing air production process, allows selection of a proper methodology for the purpose of process improvement through minimisation of the existing dispersion and process centralisation to particular defined target values.

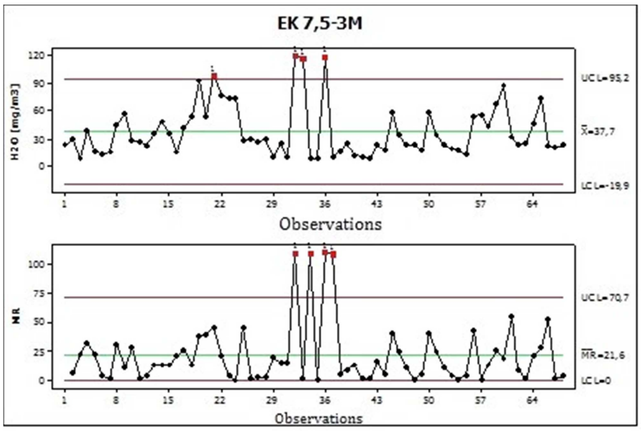

Fig. 7. Measurement data distribution obtained for the EK-7,5-3M compressor.

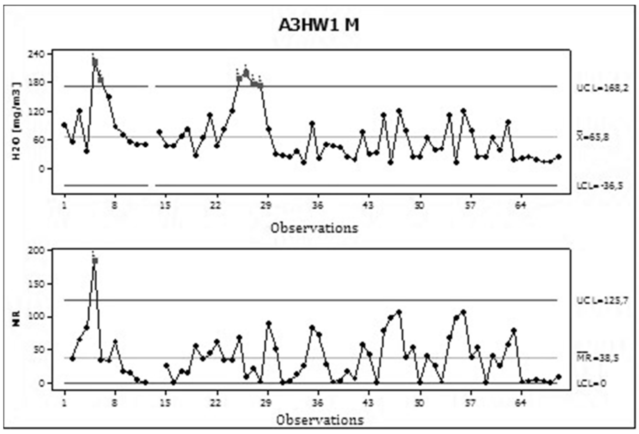

Fig. 8. Measurement data distribution obtained for the A3HW1 M compressor. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

From a qualitative point of view, in the analysis of results provided in control charts IX-MR it is observable that the results attained for the A3HW1 M compressor depart significantly from the results generated for the EK-7,5-3 M compressor, where the behaviour and measurement distribution is less dispersed. The effectiveness of breathing air treatment in a modernised compressor is higher, hence the breathing air treatment system is more efficient.

Fig.9 presents measurement results related to other supply sources and modifications in the following air treatment systems: MARINER 320E, VERTICUS BAUER 150-15-05 and EK-2-150 M.

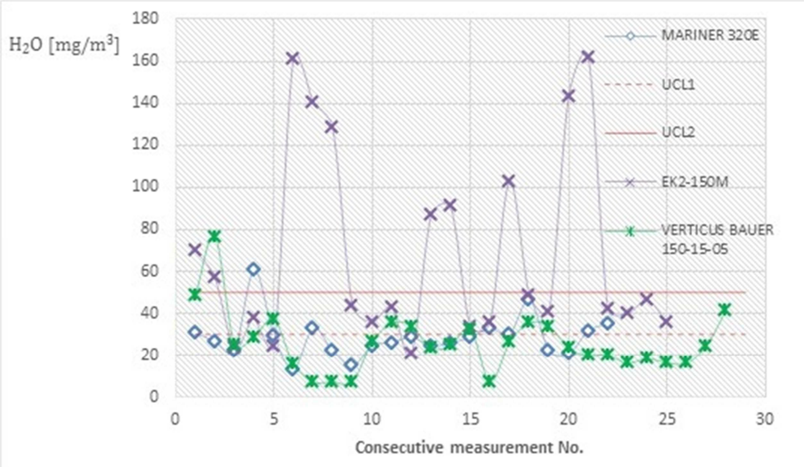

Fig. 9. Graph on consecutive measurements of H_2O content in the breathing air for various supply sources performed in the years 2002-2013. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

Results obtained for the compressor: VERTICUS BAUER 150-15-05, ensuring the highest quality breathing air is presented below in control chart IX-MR [8] for the breathing air production process (fig.10).

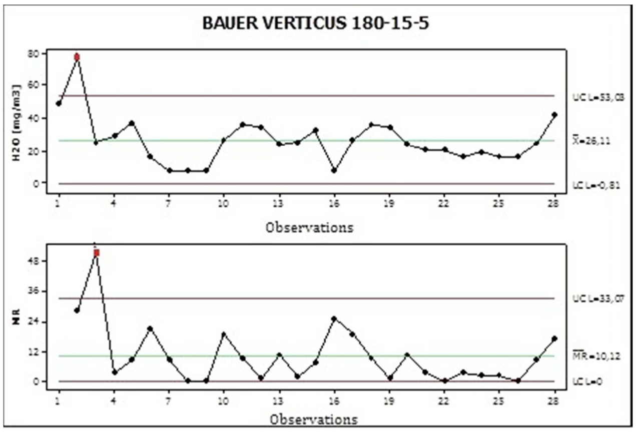

Fig.10. Distribution of measurement data obtained for the BAUER VERTICUS 180-15-5 compressor. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

It can be seen that the differences in the quality of the obtained breathing air both with the use of a new supply source and filtration system (group 3) significantly exceed the quality of air obtained with old systems (group 1) or their modernised versions[15] equipped with new filtration systems (belonging to group 2).

The general division into control groups subject to testing is presented in tab.3.

Tab. 3

General division into control groups with regard to the applied treatment system solution. Source: own study.

Type of applied solution in the breathing air treatment system	Control group
old filtration system + old supply source	1
new filtration system + old supply source	2
new filtration system + new supply source	3

The occurring quality difference in IX-MR sheets from (fig. 7, 8, 10) are easily noticeable with regard to both the quantity of measurements exceeding the defined tolerance limits and position of the centre line CL[16] in the control chart CC[17] of mean values $\bar{X}$.

The distribution of measurement data outside the tolerance limits in the chart $\bar{X}$, provides important information regarding the quantity, frequency and size of the occurring irregularities. In the new group 3 systems, in practice, preservation of proper performance approach, enables the maintaining of the process within the defined tolerance limits (LCL[18]< process <UCL[19]), with the system being less susceptible to disruptions and the impact of independent variables (e.g. temperature and atmospheric air humidity).

Group 2, representing the group of supply sources subjected to modernisation, is more efficient than group 1. Despite the application of the same type of filtration systems, the effectiveness of the air treatment system differs depending on source type. This means that even modern filtration systems are not able to ensure proper quality in configurations with overexploited supply sources without automatic drainage and control systems.

The period covered by the protective function of filtration systems in such a case is also significantly shortened due to operation in unfavourable conditions. Fig.11 & 12 below present results of consecutive measurements for the content of H_2O and CO_2 conducted for the same supply source type equipped in electric and diesel drive compressors.

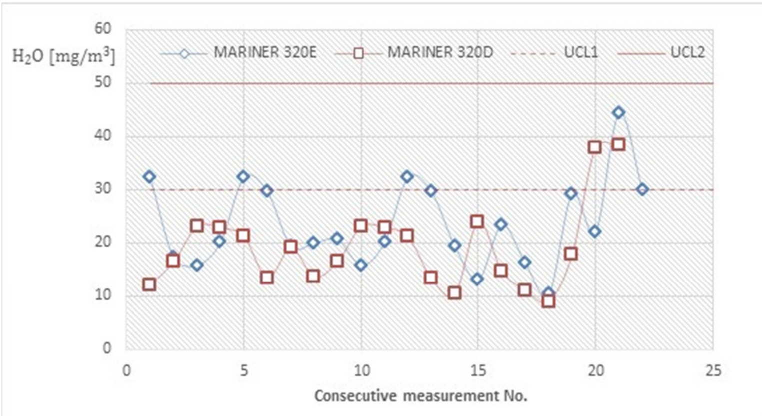

Fig. 11. Graph representing consecutive observations of measurements for the H_2O content in the breathing air for MARINER 320D/E performed in the years 2009-2013. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

It should be noted that the effectiveness of new systems, the measurement results for which are presented in fig.11, is significantly different from the quality obtained in control groups 1 and 2. The most problematic parameter - humidity content (tab.1) in the researched samples is maintained below the required values, and only in several cases exceeds the requirements for cl. I (UCL 1) breathing air.

Process stability and regularity is at an expected level despite the fact that in several cases the obtained measurement results exceed the values specified for cl. I (UCL 1).

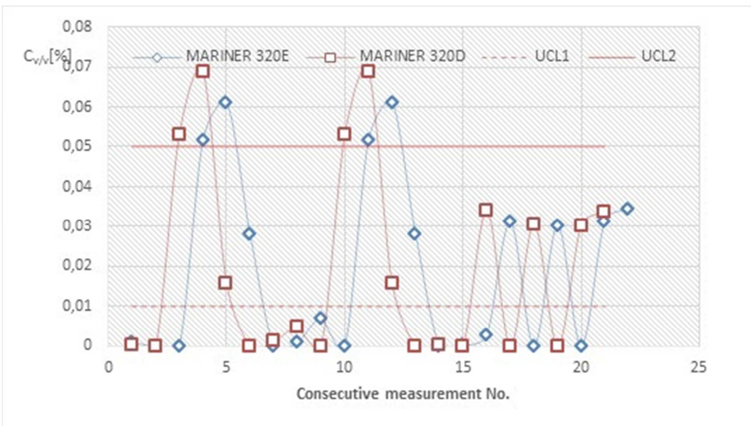

Fig. 12. Graph representing consecutive observations of measurements for the CO_2 content in the breathing air for MARINER 320D/E performed in the years 2009-2013. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

As can be seen, the measurement values obtained for the diesel compressor always slightly exceed the values obtained for the electric compressor. The use of a hopcalite insert, soda lime[20] and activated carbon in the filtration system does not fully compensate the effect of air contamination. Electric supply sources in each case indicate a lower value in CO_2 content in the examined sample.

A collective presentation of the share of measurement results failing to meet the requirements for cl. II breathing air within H_20 content in control groups 1-3 is shown in fig. 13 below.

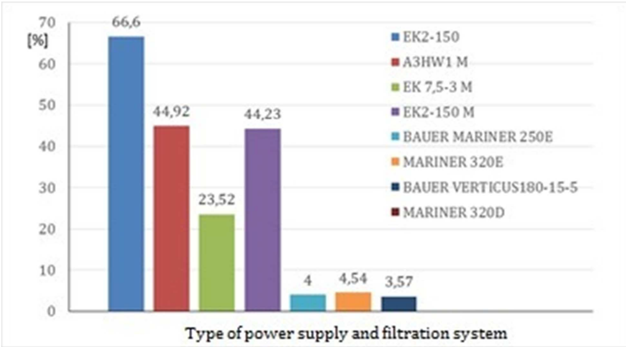

Fig. 13 Percentage share of results not meeting the requirements regarding H_20 content depending on supply source and the applied filtration system. Source: own study.

It is seen that the effectiveness of particular systems may be divided into 3 separate groups. The most efficient method consists in the application of group 3 solutions (from 0 to 4.54% share of negative results), next is group 2, depending on the technical solution (from 23.52 to 44.92% share of negative results), and the least effective system is group 1 (66.6% rejected samples).

This means that the application of solutions consisting in the use of a new filtration system and an old supply source brings the expected result of reducing the share of rejects from 66.6% to 44.23% for the same compressor type (EK 2-150 M). Moreover, it needs to be noted that the technical solution applied in group 3 produces the most expected effect, however also requires a significant financial input.

In order to resolve the current situation, applying group 2 solutions in the transitional period could reduce the number of rejects, and, in consequence, lower the expenditures related to conducting repeated physicochemical analyses. This will enable the use of resources for successive modernisation of breathing air treatment systems and implementation of new types of supply sources. In some of the analysed cases, selection of new generation filtration cartridges caused an effective reduction in the share of rejected results up to ca. 24% in the case of the Ek-7,5-3 M compressors.

Obtainment of a relatively low level of rejects gives the possibility to continue exploitation of the specified compressor type without the necessity to replace them before the lapse of nominal exploitation period. The level of obtained results for group 3 is significantly below the assumed value of 20%. Modernisation of the EK2-150 M and A3HW1 M compressors are not as effective as those implemented in the EK-7,5-3 M compressors, however they still enable the improvement of the quality of breathing air in the production process with relatively small financial inputs as compared with the purchase of new supply sources.

By comparison of the obtained results we may conclude that the most crucial result for the efficiency of breathing air treatment systems is related directly to variables (X_1, X_2, X_3, X_5) on condition of assuring proper accuracy of the performed laboratory measurements for

X_4. In such a case the effectiveness of the filtration system cleansing process significantly increases.

In the technical solutions put forward to address this problem, e.g. (WP4330 SAUER@SOHN) the residual oil content in the compressor outlet, before the air is passed through the filtration in normal conditions, i.e. at 20°C and a pressure of 1013mbar, amounts to ca. 3÷5ppm. This value is multiple times lower than that related to old type compressors: EK 2-150.

During the implementation of tests in the years 2002-2005, the results of laboratory tests obtained in a physicochemical laboratory of breathing gases (at the Central Institute of Rescue Equipment of the Polish Navy) realising chemical qualitative[21] and quantitative[22] analysis of breathing air[23], in concord with the criteria were collected and subjected to evaluation. The performed analyses explicitly indicated that the quality of the breathing air intended for hyperbaric purposes were far from the set out requirements. Fig. 14 provides a graphic representation of the results of the said evaluation.

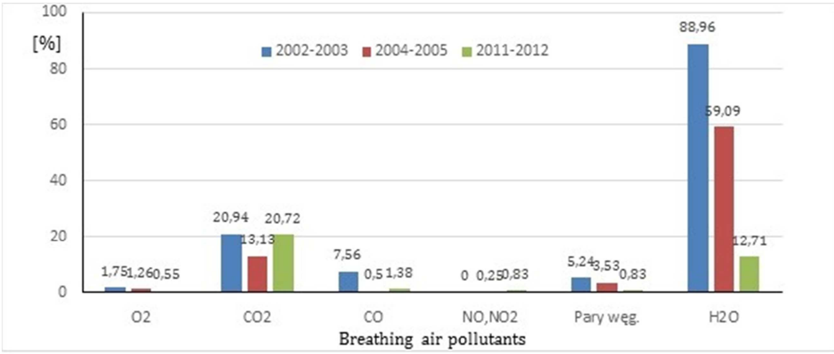

Fig. 14 The percentage share of test results on the breathing air failing to meet the quality requirements in the years 2002 – 2012. Source: own analysis on the basis of tests performed by the physicochemical laboratory at CZSRMW and measurement databases of WRTMiPP SRMDMW.

On the basis of the obtained research results modernisation works were carried out, which resulted in quality improvement in the years 2004-2005 (fig. 14). Continuation of works led to obtaining a satisfactory quality level in the years 2011-2012, which caused a multiple reduction in the share of rejected results.

Fig. 15 & 16 below present the changes occurring in the process in the 10-year observation period (between 2002 and 2013).

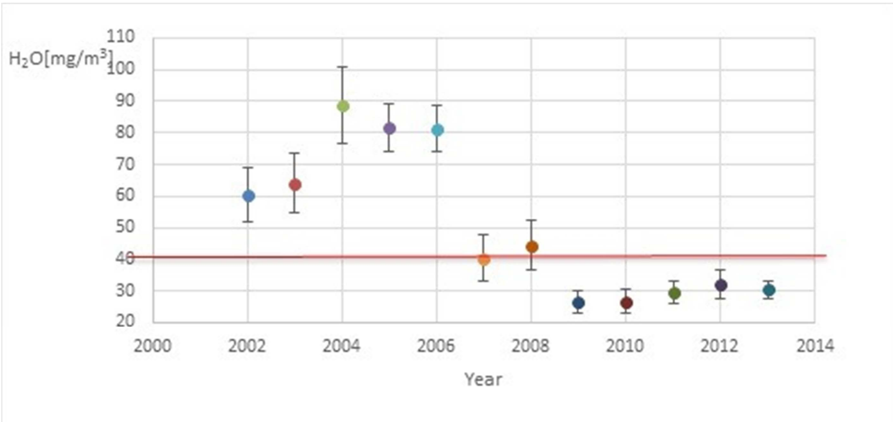

Fig. 15. Chart showing mean$\bar{X}_{2002-2013} \mp 0{,}95$ values of the confidence interval for H2O measurements. Source: own study.

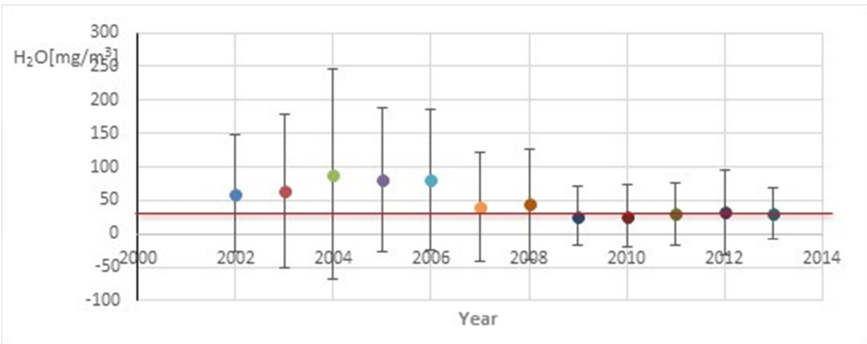

Fig. 16. Chart of mean values$\bar{X}_{2002-2013}$with expanded uncertainty for T-student distribution with k=1.96 for H2O measurements. Source: own study.

As can be seen, the provided mean values with expanded uncertainty at k=1.96 presented in fig. 16 due to their large dispersion in the years 2002-2006 are practically undistinguishable due to the accuracy of their demarcation. If we compare this with fig. 15 showing mean values with the confidence interval of 0.95 we will be able to note a certain difference.

Obtaining an answer regarding the behaviour of the analysed group of measurements required further inference, as a result of which, on the basis of historic research results, a significant difference between measurements in consecutive years was indicated. The analysis confirmed that the behaviour of the analysed statistical group was not random and the changes were caused by the introduced deterministic factors [3]. Based on the analysis of mean values along with the confidence interval defined as α=0.95 of the measurements of the tested population of results in particular years, it is possible to identify two measurement groups between which the difference occurs, namely Group A1 (2002-2006) and Group B1(2007-2013).

As a consequence of the conducted inference, a significant qualitative change was observed in relation to H_2O measurements in the years 2006-2007. It is worth noting that since that time the obtained measurement results are within the limits defined by requirements. The defined points of change also allows the performance of an evaluation of the scale of improvement and system response to the implemented changes with consideration of the necessary financial inputs.

What is important in the analysis of the measurements in group B1 is that we may conclude that the continuation of modernisation works after the year 2007 no longer caused such significant changes as it was observed earlier in the case of group A1. Further analysis and identification of variance differences in particular groups was based on a single factor variance analysis of the researched measurement population groups.

Thanks to the achievement of the intended goal it was possible to reduce the number of repeated laboratory measurements. Fig. 17 below shows the percentage share of rejected measurements in particular analysed years in accordance with the adopted assumption. The objective of activities was to reduce the percentage share of results not meeting the requirement in the researched measurement population from 89% (tab. 1) to the level of 20% of rejects.

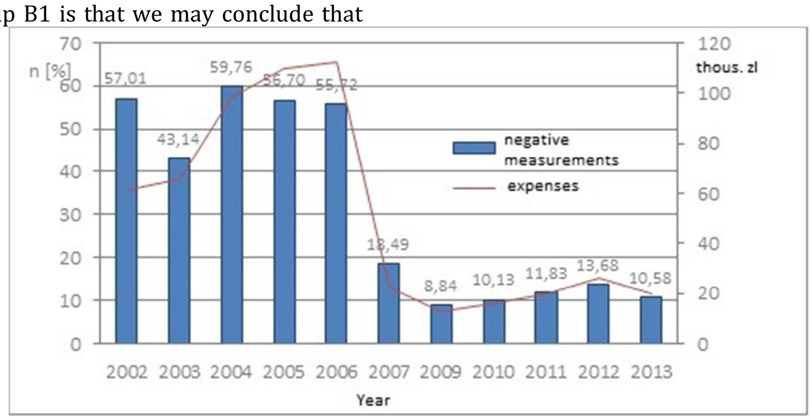

Fig. 17 The analysis of percentage share of fractions of negative results "n" in relation to H_2O content and financial inputs connected with the requirement to perform a single repeated analysis on the researched population in the years 2002-2013.

The qualitative change occurring in the analysed period is clearly visible. Since 2007 the value of the defined share of negative result fractions "n" was below the level of 20% of rejects. In the years 2009-2013 the share of samples not meeting the requirements was within 8.84-13.68%, i.e. at a much lower level than expected. The decreasing number of negative measurements led to considerable financial savings resulting from the lack of a requirement to perform repeated analyses on supply sources, which failed to meet the quality requirements.

The result of rejection of a tested sample was the necessity to implement remedial actions with regard to the tested air treatment system. In such a case, once the system was improved, in order to for it to be approved it was required to perform a repeated qualitative assessment [6]. And the repeated analysis was not always the final one. Especially in the years 2002-2006, i.e. before the introduction of a uniform sampling methodology, there were instances where corrective analyses were carried out 2 or 3 times, which had a considerable effect on the expenditures.

It should be added that the cost of the said analysis currently amounts to 900-1000 PLN (consumables, personnel, equipment, etc.[24]). In the comparison of the percentage share of rejected measurements it is necessary to analyse them in the context of the extra expense connected with the repeated performance of a control analysis. As shown in Fig.5, in the most unfavourable exploitation period in the years 2002-2006 repeated testing was required at least in 43.14% of cases. For example, in 2006 a repeated analysis was necessary with regard to ca. 112 rejected samples, which could lead to the additional spending of approx. 110 thou. PLN.

It needs to be noted that contrary to the significant quality improvement in H_2O content in the examined samples, the results regarding CO_2 content were not analogous. The CO_2 content in the entire tested population of measurement results, after the initial drop (2004-2005) returned to the previous level in the years 2011-2012, i.e. to ca. 20% of rejected measurement results. Fig. 18 below presents detailed distribution of mean measurement values in particular years with the confidence interval of ∓0,95.. Fig. 19 shows the distribution of mean values with expanded uncertainty for T-student distribution at k=1.96.

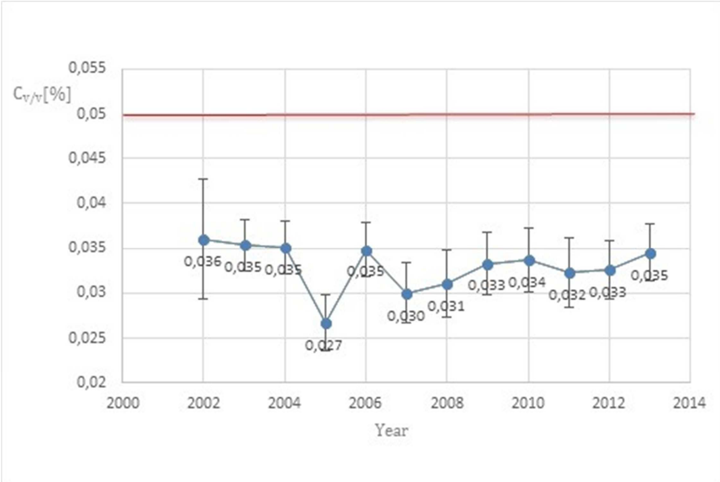

Fig. 18 Chart of mean$\bar{X}_{2002-2013}$ ∓ 0,95 confidence intervals for CO_2 measurements. Source: own study.

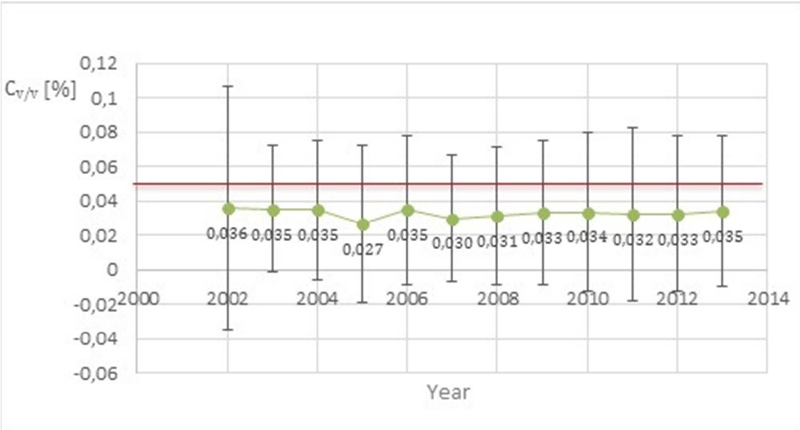

Fig. 19 Chart showing mean values$\bar{X}_{2002-2013}$with expanded uncertainty for T-student distribution at k=1.96 for CO_2 measurements. Source: own study.

As one may see, the occurring changes in the measurements of selected H_2O and CO_2 pollutants are not always unambiguous and do not provide a clear indication whether they resulted from the imposition of enforcements. CO_2 measurements are not as unequivocal as the measurement data analysis regarding H_2O.

The results of statistical inference aimed at an evaluation of the occurring differences between the discussed measurement groups will be presented in a separate article.

CONCLUSIONS

As we remember, for the need of our further works an assumption was adopted that reaching an improvement in the system response and meeting quality requirements for the entire population could be deemed satisfactory if the percentage share of results that fail to meet the requirements with regard to particular pollutants were reduced to a value of less than 20%. Taking into account the measurement results from the years 2011-2012 (fig. 15) for the entire analysed population it needs to be concluded that the intended target related to all pollutants was achieved, with an insignificant crossing of the defined threshold in CO_2 measurements (20.72%).

The distribution of the share of CO_2 results requires further analysis. Obtainment of the declared objective was a consequence of the adopted approach of modernisation works. The said works were aimed at the application of the technical solutions that had previously been subject to model and efficiency testing. The use of the discussed technical solutions in a macro scale in the tests conducted on control groups 2 and 3 with equipment unification - BAUER filtration systems - enabled the achievement of considerable savings.

As a result this led to the rationalisation of investment expenditure related to the technical modernisation of SZRP in relation to obtaining new generation supply sources. The tests allowed the selection of the 3rd control group of supply sources, which ensure much more stable breathing air production and treatment processes (MARINER 250 D/E and 320 D/E, VERTICUS 180-15-05 and SAUER @SOHN WP 5000, WP 4341).

The presented conclusions, concerning the set of variables having the greatest effect on system responses, defined the direction of technical modernisation. The defined direction consisted in the application of the 3rd group of solutions and the necessity to replace overexploited devices, coupled with the stop gap solution of implementing group 2 solutions in the systems allowing for modernisation (EK2-150, EK 7,5-3, A3HW1 compressors).

The application of group 2 systems enabled a double reduction of incorrect results as compared with group 1 corresponding to the initial state. Research results constituted the basis for the implementation of further modernisation works. Fig. 20-23 below present selected examples of the implementation of a container set PZZP[25] by SRM DMW for use at SZRP as well as modernisation of ORTOLAN bases in the Polish Navy.

Fig. 20 General view of the interior of the Mobile Air Supply Set. Source: own study.

Fig. 21 General view of the Mobile Air Supply Set container. Source: own study.

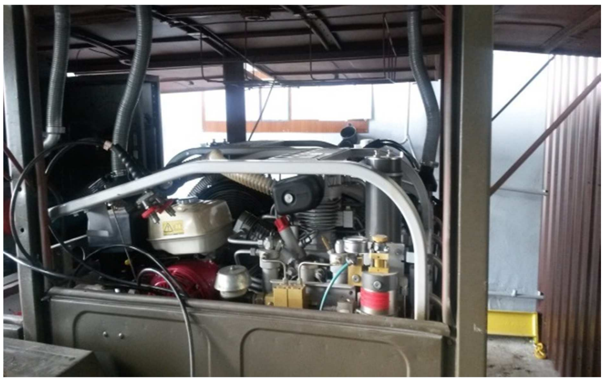

Fig. 22 View of the interior of the supply system for an ORTOLAN base securing underwater works equipped in MARINER 320 D compressors. Source: own study.

Fig. 23 General view of the supply system for an ORTOLAN base securing underwater works. Source: own study.

Modernisation of supply systems of ORTOLAN bases securing underwater works was carried out within the technical solutions from groups 2 and 3.

The application of optimisation methods [14] allowed the achievement of measurable results of the undertaken actions. Maintenance of quality through continuous monitoring of the production process as well as its control through ensuring proper quality of laboratory measurements made it possible to guarantee proper conditions for control of the technical process.

In the course of tests on the discussed process a wide range of tools was used related to quality management and risk assessment [12,8,15], with the most important ones including:

- ISHIKAWA cause and effect diagram;
- PARETO analysis[26];
- FMEA analysis (Failure Mode and Effect Analysis);
- QFD methods (Quality Function Deployment);
- histograms;
- control charts (SPC);
- Data Mining methods.

It should be added that their application allowed effective process management [16,13,15] and its control. The discussed methods proved to be extremely useful.

Upon research completion and commencement of continuation of works in the specified direction, consisting in successive modernisation and replacement of devices, a significant element was performance of statistical inference allowing an assessment of the changes occurring in the process.

The process of data assessment and analysis was conducted on the basis of quarterly reports and collecting measurement results on the researched population in the database of WRTMiPP SRM DMW. The presented effectiveness assessment regarding the selection of technical devices and the works performed allowed the obtainment in 2012 of the declared criteria of achieving air purity levels of $C_i \leq 20\%$. Only in the case of CO_2 measurements the quantity of rejects amounted to 20.72%.

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mgr inż. Arkadiusz Woźniak
Zakład Technologii Prac Podwodnych
Akademii Marynarki Wojennej
ul. Śmidowicza 69,
81-103 Gdynia
tel. 261262746
e-mail: ar.wozniak@amw.gdynia.pl

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[1] SZRP – the Armed Forces of the Republic of Poland,
[2] Absorption - gas absorption by a liquid - or rarer - gas or liquid absorption by a solid is a process occurring in the entire absorbent mass,
[3] Adsorption - gas absorption by a liquid - or rarer - gas or liquid absorption by a solid, is a process occurring on the surface of an absorbent,
[4] MWRP - the Navy of the Republic of Poland,
[5] AC-activated carbon,
[6] MS-molecular sieves,
[7] HP-Hopcalite (mix of MnO_2,CuO,CO_2O_3,Ag_2O),
[8] FID (Flame Ionization Detector),
[9] PDD(Pulsed Discharge Detector),
[10] FTIR(Fourier Transform Infrared Spectroscopy),
[11] C_i-initial parameter (measurement of the content of i-th contamination of the breathing air $C_{H_2O}, C_{CO}, C_{CO_2}, C_{CH_4}, C_{NO_X}$ in the examined sample, after the filtration system),
[12] WRTMiPP SRMDMW- Department of Rescue of Maritime Technique and Underwater Works of the Naval Command of Maritime Rescue,
[13] SPC - Statistical Process Control,
[14] MR - Moving Range – the absolute value of difference between two consecutive measurements in neighbouring samples,
[15] marked with letter "M",
[16] CL - Centre Line – indicates the calculated mean value $\bar{X}$ for the considered measurement group,
[17] CC - Control Chart,
[18] LCL - Lower Control Limit - a calculated or defined value regarding the considered measurement group - in the discussed case 0mg/m^3 H_2O,
[19] UCL - Upper Control Limit - a calculated or defined value regarding the considered measurement group - in the discussed case 50mg/m^3 H_2O for cl.II, 35mg/m^3 H_2O for cl. I acc. to NO-07-A005:2010,
[20] Soda lime (mix of NaOH, Ca $(OH)_2$, H_2O),
[21] Chemical qualitative analysis - a set of techniques enabling specification of the chemical composition of the examined mixes chemical compounds,
[22] Chemical quantitative analysis - a set of techniques allowing to determine the numerical values (expressed with the use of suitable units of measurement, for instancein grams or other(sub)quantities) of the chemical composition of the mixes subject to testing,
[23] NO-07-A005:2010 Diving for military purposes Breathing mixes for divers Classification, requirements and research,
[24] according to offers available on the market with regard to qualitative-quantitative determination of contaminants in the breathing air pursuant to NO-07-A005,
[25] PZZP - Mobile Air Supply Set,
[26] PARETO analysis - also known as the ABC method.