Original article

Rules for fitting filtering gas masks

Władysław Harmata[1]* , Dorota Kamionek[2]

[1] Faculty of New Technologies and Chemistry, Military University of Technology, Warsaw, Poland,
  e-mail: wladyslaw.harmata@wat.edu.pl

[2] Military Institute of Chemistry and Radiometry, Warsaw, Poland,
  e-mail: d.kamionek@wichir.waw.pl

INFORMATION	ABSTRACT
	The paper presents the results of research on fitting modern filtering masks using the optoelectronic method during long-term use. They were analyzed and compared with the testing results applying the reference method – total inward leakage.
	KEYWORDS

Introduction

Contamination of the atmosphere with suspended dust, which is part of smog, is the bane of modern times. Breathing polluted air is a way to worsen symptoms of asthma, chronic obstructive pulmonary disease, or respiratory tract infections, and increase the incidence of these diseases. Not only particulate matter but also ozone, nitrogen oxides, sulfur dioxide, and carcinogenic substances from the group of polycyclic aromatic hydrocarbons (PAHs) or dioxins, is to blame [1]. Unfortunately, research by the World Health Organization (WHO) shows that one can talk about the risk of death due to smog. The air pollution effects turn out to be deplorable: in 2010 alone, it caused 230,000 deaths from lung cancer. In Poland, due to smog, there are nearly 45 thousand premature deaths per year. When it comes to smog-related mortality, the effects relate more often to the loss of healthy years than the years alone – we live a year or two shorter due to pollution, but spend the last years in a much worse health condition [1]. Prof. Tadeusz Zielonka, pulmonologist, said, "smog kills". When asked how we can protect ourselves from smog, the doctor replies that one solution does not exist, and a comprehensive approach is necessary; the tasks are to be fulfilled by the government and local governments. He mentioned education, social awareness, and the issue of respecting the rules by people as essential. Filtering masks protect against smog temporarily, but not every model will perform its function well. The expert said that masks should not be ordered online since they must be well-fitted and tight. *Masks are not for men with facial hair* – warned the doctor. As he noted, masks should have dust and gas filters [2].

Recent months have been the experience of communities around the world with the coronavirus (SARS-CoV-2). The virus is most often transmitted by droplet infection, i.e., when sneezing, coughing, etc. It can cause aerosol infections, i.e., indirectly and by sticking to dust particles, etc.

The basics of protection against contamination of the Polish Armed Forces soldiers are included in the doctrinal document of the chemical troops, namely "Defense against weapons of mass destruction in combined operations DD/3.8(A)" [3].

Section 3.4 of the document defines "protection against contamination is a project consisting in the maximum use of the functional features of individual and collective means of protection against contamination and the protective properties of combat equipment, engineering facilities, and the area". Protection against contamination aims to increase the military's ability to survive. Individual protection against contamination plays the most important role in the protection of the human respiratory system. According to DD/3.8(A), it is an activity consisting in equipping each soldier with a filtering gas mask and insulation or filtering skin protection measures to ensure his/her safety during the performance of tasks in conditions of risk of contamination or contamination [3].

The provisions of the DD/3.8(A) are unambiguous but not relevant to user safety. This work presents the problems of fitting a gas filter mask during long-term use.

Increasing industrialization, technological development, and wider use of nuclear, biological, and chemical materials increase the risk of their release to the environment, most often in the form of dust [4].

It is true that the SARS-CoV-2 coronavirus that causes the COVID-19 disease did not spread by itself, but was spread by humans via droplets when sneezing or coughing [2].

Equipping an employee (rescuer) with respiratory protection equipment does not solve the problem. An improperly selected mask (half-mask) in terms of its protective properties (class of filter or absorber) or poorly suited to the shape and dimensions of the face may have worse effects than its absence. This is particularly important nowadays, especially in the case of medical services operating in the environment of exposure to infectious agents.

1. Gas masks

Toxic agents can enter the human body through various routes, most often respiratory, digestive and skin ones. However, the respiratory system is most at risk. In an adult, the gas exchange area ranges from 75 to 100 m² and it is the thinnest membrane through which gases enter the bloodstream. In addition, there is a possibility of contamination with dusts (aerosols), e.g., fine PM2.5 (particle diameter 2.5 µm), submicron PM1 (particle diameter below 1.0 µm), and ultrafine PM0.1 (particle diameter below 0.1 µm) [5]. In such a situation, respiratory protection is especially crucial. In the construction of modern filtering gas masks, great importance is attached to the anatomical mask structure, so that it fits the shape of almost every face and does not cause pressure and negative consequences associated with them. It was possible thanks to the involvement of anthropologists in the design of masks. Their task is to develop, from mass anthropometric measurements, arrangements of dimensional features of the head in the population of potential mask users. On the basis of these arrangements, phantoms for this population are designed in a number that corresponds closely to the designed number of face part sizes.

Analysis of information on filter gas masks designed and produced in technically developed countries allows identifying trends and tendencies regarding gas masks. They can be presented as follows:

– anatomical facial parts are used. This affects the adhesion of the mask to the user's face, reduces pressure and increases the effectiveness of protection,

– additional seals are commonly used on the face adjacent part. They are made in the form of a "collar" wrapped around the mask cavities or a skirt attached to the contact surface. The collar is concave, stiff, or flexible. Additional seals reduce pressure and improve protective properties. However, it is more preferred to use flexible seals,

– breathing resistance in the mask makes it impossible to perform heavy physical work, let alone operate in combat conditions. The reduction in exhalation resistance is achieved by increasing the diameter of the leaflet and the exhalation valve; however, excessive increase in the diameter of the leaflet can cause severe disruption to the valve and increase internal leakage. The design of the combined filter may affect the amount of resistance. Masks with two combined filters have lower inhalation resistance, because they can work simultaneously. In the mask, it is possible to replace the filter absorbers without holding your breath [6].

Figure 1 shows examples of modern filtering gas masks.

2. Anti-dust half masks

Disposable anti-dust half masks and filtering masks, depending on the selected model, are used to protect the respiratory tract against solid contaminants of various origins, and those with a carbon cartridge – also against odors and acid gases below TLV[1]. Medical surgical masks protect the organism from biological hazards. Depending on the degree and type of dustiness, the anti-dust respirators are available in P1, P2, P3 classes with and without exhalation valves.

Based on the EN-149:2001 + A1:2009 Standard, three classes are distinguished depending on the effectiveness of protection:

– class 1 – (FFP1) – basic filtration efficiency (at the level of 80% for solid particles with a diameter of 0.6 μm), protection against solid and liquid particles (dust, smoke, mists) with low toxicity, and the maximum concentration of the substance is at most 4×TLV,

– class 2 – (FFP2) – average filtration efficiency (94% for solid particles with a diameter of 0.6 μm) for protection against solid and liquid particles of low or medium toxicity, the maximum concentration does not exceed 10×TLV,

– class 3 – (FFP3) – high level of filtration (99% for solid particles with a diameter of 0.6 μm) for protection against highly toxic solid or liquid particles, if the maximum concentration is 30×TLV [11].

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[1] The maximum permissible concentration (TLV – threshold limit value) is the weighted average value of the concentration, the impact of which on the employee during the 8-hour daily and average weekly working time, specified in the Act of June 26, 1974 – Labor Code [Ustawa z dnia 26 czerwca 1974 r. Kodeks pracy (Dz. U. 1974 Nr 24, poz. 141)], during the period of his/her professional activity does not should cause negative changes in his/her health and the health of his/her future generations. Regulation of the Minister of Family, Labor, and Social Policy of June 12, 2018, on the highest allowable concentrations and intensities of factors harmful to health in the work environment, Journal of Laws, item 1286 [Rozporządzenie Ministra Rodziny, Pracy i Polityki Społecznej z dnia 12 czerwca 2018 r. w sprawie najwyższych dopuszczalnych stężeń i natężeń czynników szkodliwych dla zdrowia w środowisku pracy (Dz. U. 2018, poz. 1286)].

Fig. 1. Examples of modern filtering gas masks: a) American MCU-2/P – naval and air forces,
b) Finnish Scott Health & Safety M 95 NBC mask, c) Polish MP-6, d) British GSR,
e) American M50 mask
Source: [7-10, Scott Health & Safety materials].

FFP3 protection measures were recommended by the PZH National Institute of Public Health for paramedics, who may have contact with SARS-CoV-2 [12]. However, it is necessary to maintain other elements of hygiene – first, avoid touching the eyes, mouth, nose, wash hands regularly, avoid public places, react to the emergence of a threat in the immediate vicinity. The mask will not fulfill its function if it is not properly fitted to the face. Therefore, when buying, one need to pay attention to size. The most commonly used numbering is known from clothes – from "S" to "XL" [13]. This is usually, unfortunately, the only information about fitting.

3. Mask and half mask inward leakage

When determining the requirements for the protective properties of gas filtering masks, it is necessary to take into account the interdependence of the parameters that determine the necessary degree of respiratory protection against chemical, radioactive, and biological substances.

Aerosols can penetrate the combined filter, but can mainly be sucked in by leaks in the face part and its connections between its components – Figure 2.

When inhaled, contaminated air can penetrate into the space under the mask through the following routes:

1) leaks caused by poor adhesion of the face part to the face in the sealing belt (incorrect mask fitting), passing through the forehead, temples, chin), ⟶

2) leaks caused by the delay in closing the exhalation valve at the transition from exhalation to inhalation, ⟶

3) due to leaks at the connection points of individual parts of the mask:
   – with a combined filter, ⟶
   – with a sound chamber, ⟶
   – with a drinking device – UPP, ⟶
   – with the doughnut knot. ⟶

Fig. 2. Hypothetical points of penetration of toxic aerosols through the components of modern filtering gas masks
Source: Own study.

During inhalation, a negative pressure is created under the mask; the outside air flows into the space under the mask through the combined filter as well as through leaks. The amount of this air increases with growing vacuum under the mask. On exhalation, the air is expelled and a positive pressure is created.

The PN-EN-136:2001 Standard requires that "the average value of the internal leakage of the test substance in the inhaled air should not exceed 0.05% for any of the ten test participants in any exercise" [14].

The NO-42-A214:2017 Defense Standard requires that "the total internal leakage of the gas mask in relation to the test contaminant should be less than 0.01%" [15].

The greatest danger posed by sucking in is the ingress of contaminated air through the exhalation valve. Sucking through other possible leaks of the mask parts can be relatively easily reduced, and often practically excluded.

The exhalation valve closes and opens due to pressure changes in the space under the mask, hence there will always be some delay in opening and closing the valve. Unfortunately, because of that, there is a probability of contaminated air penetrating into the volume under the mask.

4. Analysis of fitting methods

As mentioned in the above considerations, the Polish Armed Forces lack clear requirements for ISOPS fitting methods. The standards provide information on laboratory tests of mask tightness (fit tests). They require the use of specialized apparatus and properly trained personnel, which means that they cannot be performed directly, e.g., in the armed forces.

The standard PN-EN 136:2001 [14] contains the following requirements:

- tightness – leakage of the mask should not exceed the pressure change by 1 mbar within 1 minute during the test at a negative pressure of 10 mbar,
- inward leakage – the mask should fit the contours of the face. The mean value of the inward leakage of the test substance in the inhaled air should not exceed 0.05% for any of the ten test subjects in any exercise.

The defense standard NO-42-A214:2017 [15] contains the following requirements:

- face fit – the gas mask face piece size range should ensure fitting for 98% of potential users from the Polish population, with the number of sizes not exceeding 4. The gas mask fitting factor (fit factor) should not be less than 10,000,
- time to put on a mask – changing the position of the gas mask from the marching in combat one (time to put on a mask) should be done in less than 9 s. If the gas mask is equipped with a protective hood, the total time for applying the mask and the hood should not exceed 15 s,
- the possibility of a long stay in the gas mask – the gas mask should allow the user to stay uninterrupted in it for 24 hours, while the period of uninterrupted wear should include intensive physical work (from 4 h to 5 h), fluid intake via the UPP, and about 6 h of sleep,
- static tightness – total leakage into the gas mask should not cause a pressure change of more than 0.5 mbar within 1 minute during the test with negative pressure under of 10 mbar the mask,
- static tightness of a gas mask with the UPP connected – a gas mask with the connected UPP (ready for fluid intake) should remain statically tight,

 – total inward leakage – the leakage of the gas mask relative to the test contamination
   should be less than 0.01%.

In the Polish Armed Forces, the so-called individual and mass adjustment of filtering gas masks is mostly carried out using the so-called chemical method.

Chloropicrin is the test agent used to contaminate the air in the lampshade chamber (in UST-41/Ch and NS-64 tents) when checking the masks. From the safety data sheet of this hazardous substance, prepared by the Central Institute for Labor Protection, one can obtain toxicological information of chloropicrin – toxic and other harmful biological effects on the human system: a very toxic, highly irritating substance [16].

The mask fit factor using chloropicrin is estimated at 1,000, with 10,000 required in NO-42-A214:2017 [17].

The second method of matching masks used in the Polish Armed Forces is the CS method (2-[(2-chlorophenyl)methylidene]propanedinitrile) in KG-12 chambers. In concentrations of 0.001 mg/dm³, CS causes severe irritation of the upper respiratory tract and eyes, while the concentration of 0.005 mg/dm³ is considered the limit of resistance. The lethal concentration of CS is 25 mg/dm³. Symptoms of irritation (poisoning) develop after a very short latency period, depending on the CS concentration, from several seconds to several minutes, causing burning, lacrimation, pain in the nasopharynx, sneezing, coughing, profuse runny nose, drooling, nausea, and vomiting. It is accompanied by headaches and toothaches, pain in the ears, behind the breastbone, and sometimes stomach pains. In light poisoning, the symptoms of irritation intensify within several minutes after putting on the gas mask or after leaving the contaminated atmosphere. After 1-3 hours, symptoms begin to regress [18].

The mask fit factor using CS is estimated at 3,000, with 10,000 required in NO-42-A214:2017 [17].

In NATO Armed Forces and in domestic factory and research laboratories, the fitting of filtering gas masks is performed using the optoelectronic method (a detector with a laser diode) with PortaCount leak testers. The device determines the ratio of air dustiness outside and inside the mask (worn on the user's head) and gives this value of the so-called fit factor. The measurement is performed by counting the particles in the gas taken outside and inside the mask (a special valve changes the gas sampling path). For example, a fit factor of 10,000 units means that 1 atomic aerosol particle was recorded in the volume under the mask in relation to 10,000 aerosol (dust) particles in the air outside the mask [19].

In the PN-EN 136:2001 Standard it is assumed that the maximum time of using the mask is 8 hours (shift time), and in the NO-42-A214:2017 Standard this time is set at 24 hours (including 6 hours of sleep). There is no requirement in both documents to verify the fit during or after the service life.

5. Tests of fitting the selected filtering masks depending on the time of use and other parameters

5.1. Research methodology

The research was carried out over eight days with the use of MP-6 filtering masks (introduced to the Polish Armed Forces in 2011), MP-5 masks (successively withdrawn from the Polish Armed Forces) and Promask masks (civilian ones). During the research, the results were

influenced by the tested people's growing facial hair over the days, the appearance of sweat, fatigue, and other physiological factors.

The fitting of masks with the use of chloropicrin was carried out in accordance with the methodology contained in the 361/89 NBC Defense Manual "Checking the tightness and fitting of gas masks" [20].

Before testing for total inward leakage, participants were fitted with an optoelectronic mask. The PortaCount Pro instrument used in the test allows checking the fit of the gas mask by comparing the concentration of ambient particles to the concentration of particles under the mask. The ratio of these two concentrations is called the fit factor.

The reference method, consisting in determining the total inward leakage, was carried out for various exercises specified in the PN-EN 13274-1:2004 Standard according to accredited test procedure at the Military Institute of Chemistry and Radiometry [21].

5.2. Results of fitting gas masks with chloropicrin

It was assumed that all tested gas masks are well fitted, after their tightness has been checked by users in a lampshade chamber. There were no symptoms of chloropicrin getting under the mask.

All gas masks used were tested with the PortaCount and their total inward leakage was determined. The results are shown in Tables 1 and 2 and Figures 3 and 4.

5.3. Results of tests on fitting masks with the optoelectronic method

The mean of the results of testing 2 gas masks is presented in Table 3 and Figure 5.

Table 1. Fit factor

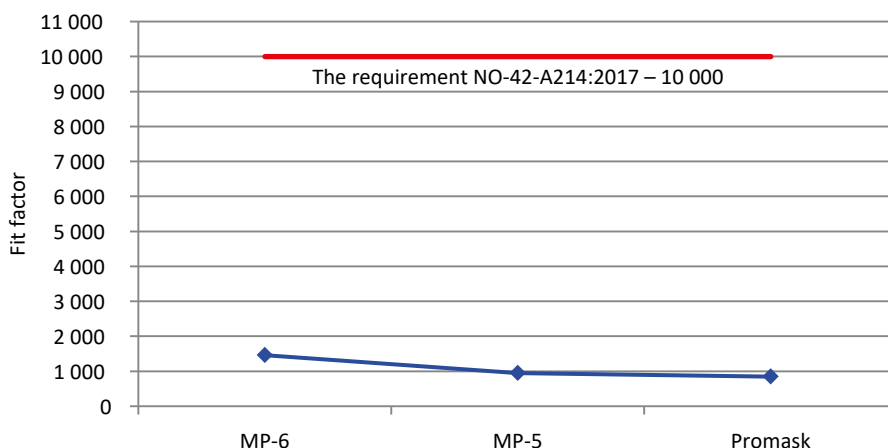|	**MP-6**	**MP-5**	**Promask**
Fit factor	1460	950	850

Source: Own study.

Fig. 3. Results of fitting the mask using the optoelectronic method
Source: Own study.

Table 2. Total inward leakage of selected gas masks during the given activity

Activity	MP-6	MP-5	Promask
march 1	0.017	0.018	0.02
head shaking	0.015	0.028	0.031
head nodding	0.035	0.122	0.15
recitation	0.015	0.079	0.031
march 2	0.028	0.071	0.034

Source: Own study.
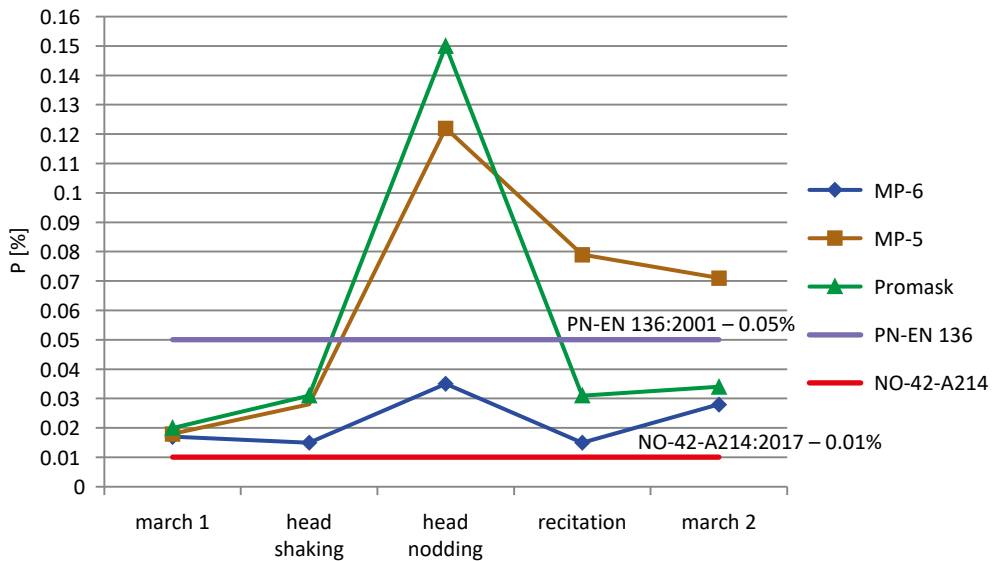
Fig. 4. Diagram of total inward leakage dependence on the type of activity
Source: Own study.

5.4. Results of mask fitting tests by total inward leakage

The mean of the results of testing 2 gas masks for the march 1 exercise is presented in Table 4 and Figure 6.

The mean of the results of testing 2 masks for the right-left head shaking exercise is presented in Table 5 and Figure 7.

The mean of the results of testing 2 masks for the head nodding exercise is presented in Table 6 and Figure 8.

The mean of the results of testing 2 masks for the recitation exercise is presented in Table 7 and Figure 9.

The mean of the results of testing 2 masks for the march 2 exercise is presented in Table 8 and Figure 10.

Table 3. Fit factor

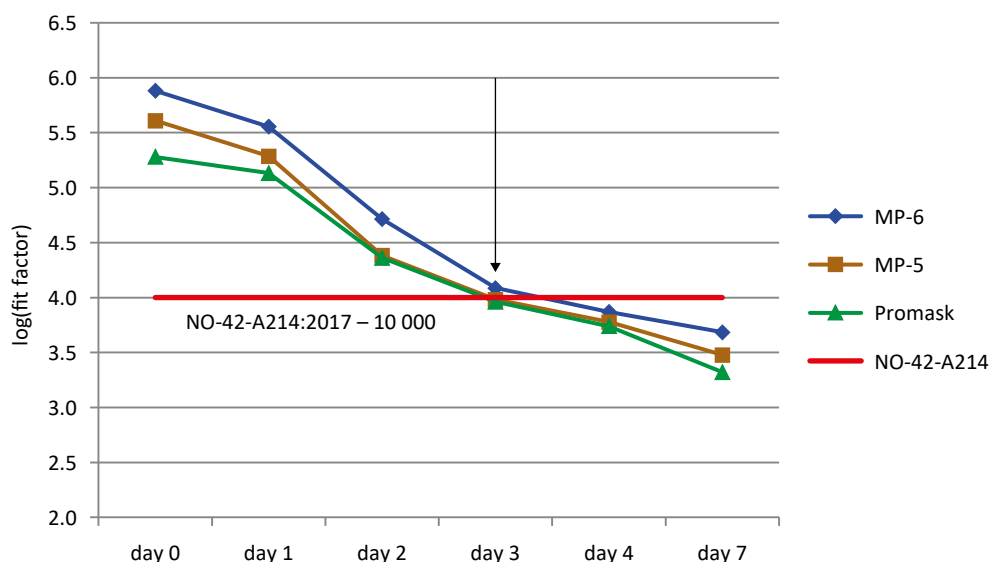|	**MP-6**	**MP-5**	**Promask**
day 0	760 500	407 000	190 000
day 1	360 000	193 500	135 500
day 2	51 800	24 150	22 900
day 3	12 200	9 600	9 150
day 4	7 415	5 995	5 475
day 7	4 840	3 005	2 096

Source: Own study.

Fig. 5. Fit factor for the tested masks
Source: Own study.

Conclusion

The problem of fitting filtering gas masks concerns both workplaces (employees) and uniformed services (soldiers, police officers, firefighters), and now also the public due to air pollution in the form of smog, and now also coronavirus.

While respiratory protection measures used at workplaces relate to one or several substances, for measures intended for uniformed services, the amounts can be estimated with some probability at most.

As mentioned, in NATO Armed Forces and in national factory and research laboratories, mask fitting is performed using the optoelectronic method (a laser diode detector) with the use of PortaCount devices. It is a quick method that produces the result of the fit factor.

In the Polish Armed Forces, masks are fitted with the so-called chemical method using chloropicrin or CS as the test agent.

Table 4. Total inward leakage test results – march 1

	MP-6	**MP-5**	**Promask**
day 0	0.00025	0.00045	0.0005
day 1	0.00085	0.00095	0.0011
day 2	0.00815	0.0089	0.0103
day 3	0.0137	0.01895	0.01965
day 4	0.547	0.6585	0.78
day 7	2.665	3.1575	3.355

Source: Own study.
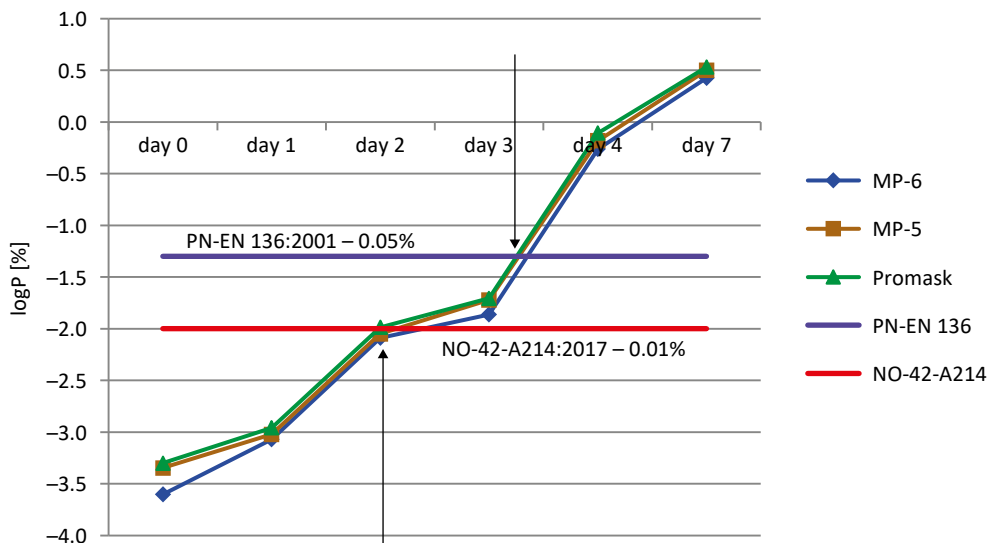
Fig. 6. Results of total inward leakage tests of the mask with 0-7-day facial hair
Source: Own study.

Before testing for total inward leakage, participants' masks were fitted with an optoelectronic method. Fit factors determined for all tested masks were many times greater than required by the standard (e.g., for the MP-6 mask, approx. 700,000). The required value of the fit factor was maintained for 3 consecutive days for the MP-6 mask and for 2 consecutive days for the MP-5 and Promask masks.

The reference method, consisting in the determination of the total inward leakage, was carried out for various exercises specified in the PN-EN 13274-1:2004 Standard.

For the exercise – march 1 (at the speed of about 6 km/h) the following results were obtained:
- – meeting the requirements of NO-42-A214:2017 (P = 0.01%) for 3 consecutive days by the MP-6 and MP-5 masks and for 2 consecutive days by the Promask mask,
- – meeting the requirements of PN-EN 136:2001 (P = 0.05%) for 3 consecutive days by all masks.

Table 5. Total inward leakage test results – right-left head shaking

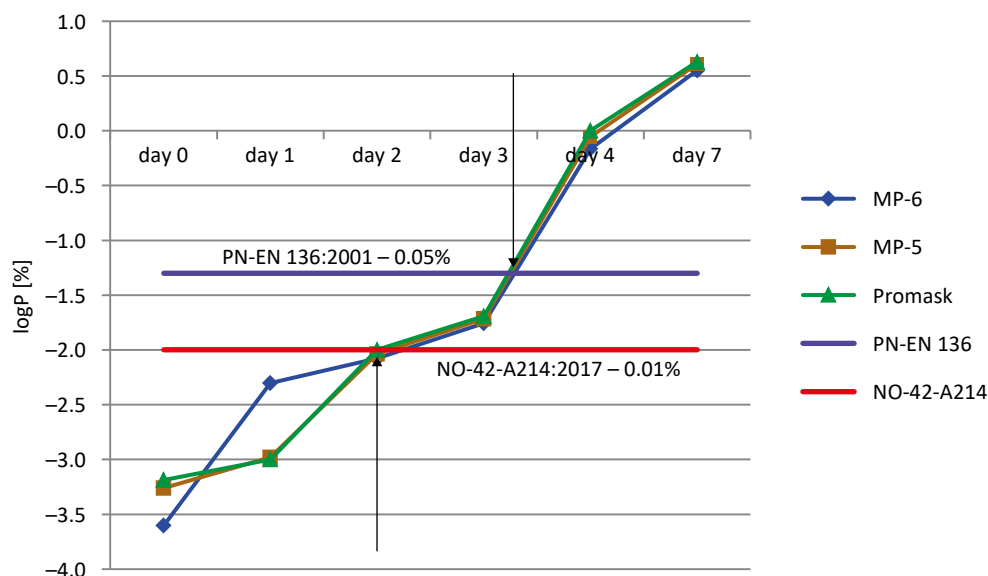|	MP-6	MP-5	Promask
day 0	0.00025	0.00055	0.00065
day 1	0.005	0.00105	0.001
day 2	0.00835	0.0092	0.01
day 3	0.01755	0.0193	0.0203
day 4	0.6855	0.885	1.005
day 7	3.56	4.07	4.245

Source: Own study.

Fig. 7. Results of total inward leakage tests of the mask with 0-7-day facial hair
Source: Own study.

For the exercise – right-left head shaking it was obtained:
- – meeting the requirements of NO-42-A214:2017 (P = 0.01%) for 3 consecutive days by the tested masks,
- – meeting the requirements of PN-EN 136:2001 (P = 0.05%) for 4 consecutive days by all masks.

For the exercise – head nodding, the following results was obtained:
- – meeting the requirements of NO-42-A214:2017 (P = 0.01%) for 3 consecutive days by the MP-6 mask and for 2 consecutive days by the MP-5 and Promask masks,
- – meeting the requirements of PN-EN 136:2001 (P = 0.05%) for 4 consecutive days by all masks.

Table 6. Total inward leakage test results – head nodding

	MP-6	MP-5	Promask
day 0	0.00055	0.00045	0.00065
day 1	0.00105	0.0011	0.00105
day 2	0.0093	0.0102	0.01045
day 3	0.01865	0.02065	0.0198
day 4	0.99	1.155	1.22
day 7	4.08	4.44	4.48

Source: Own study.
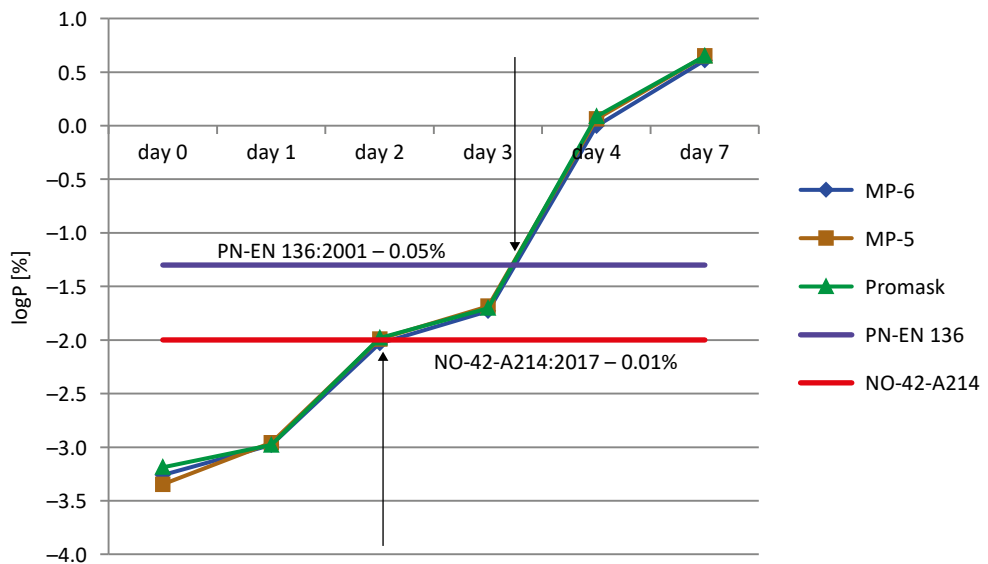
Fig. 8. Results of total inward leakage tests of the mask with 0-7-day facial hair
Source: Own study.

For the exercise – recitation, the obtained results were as follows:
- meeting the requirements of NO-42-A214:2017 (P = 0.01%) for 2 consecutive days by all tested masks,
- meeting the requirements of PN-EN 136:2001 (P = 0.05%) for 4 consecutive days by all masks.

For the exercise – march 2, it was obtained:
- meeting the requirements of NO-42-A214:2017 (P = 0.01%) for 3 consecutive days by the MP-6 mask and for 2 consecutive days by the MP-5 and Promask masks,
- meeting the requirements of PN-EN 136:2001 (P = 0.05%) for 4 consecutive days by all masks.

The control of the fitting of masks with a chemical method commonly used in the Polish Armed Forces was to give the answer whether it was sufficient for a proper fitting. During the tests, it was found that all the masks were well-fitted – no irritating effects of chloropicrin

Table 7. Total inward leakage test results – recitation

	MP-6	MP-5	Promask
day 0	0.00085	0.00505	0.0013
day 1	0.0014	0.0027	0.0026
day 2	0.01015	0.0132	0.0118
day 3	0.02445	0.0339	0.0304
day 4	1.305	1.535	1.295
day 7	5.945	5.785	5.535

Source: Own study.
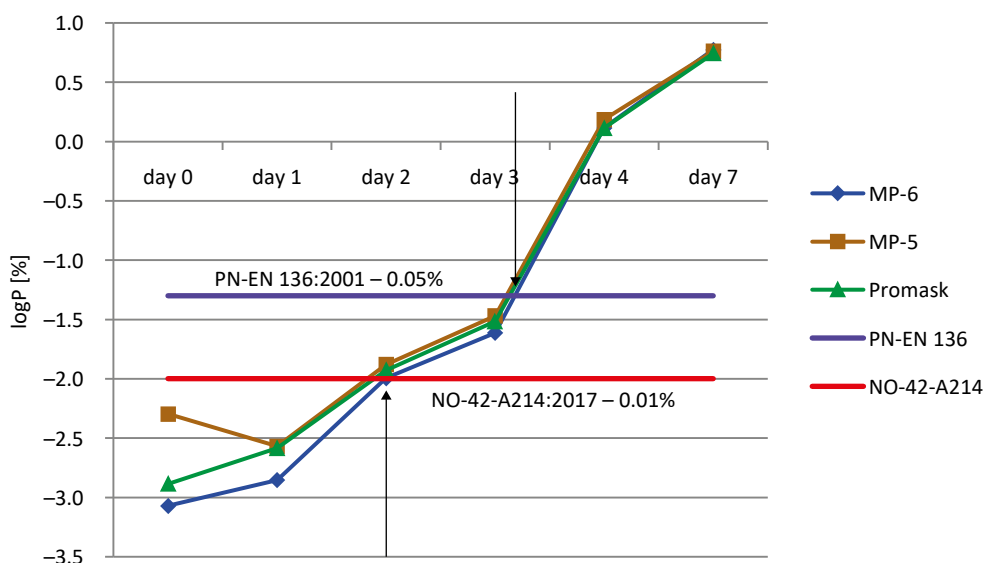
Fig. 9. Results of total inward leakage tests of the mask with 0-7-day facial hair
Source: Own study.

(eyeballing, burning sensation) were identified. The tests conducted with the use of the opto-electronic method and the total inward leakage proved that the requirements of the defense standard NO-42-A214:2017 with regard to the obtained fit factor and total inward leakage for all tested masks were not met.

The period of use of the masks (24 h) specified in NO-42-A214:2017 may be extended to 48 hours without the observed mask unsealing.

Conclusions

1. The analysis of contemporary anthropogenic and natural hazards shows that there is a constant need to improve individual respiratory protection measures, mainly against smog, toxic chemical, and biological substances.

2. The method of fitting masks with chloropicrin or CS, still used in the Polish Armed Forces, does not meet the requirements of the relevant standards. Additionally, it is not specified

Table 8. Total inward leakage test results – march 2

	MP-6	**MP-5**	**Promask**
day 0	0.00035	0.0005	0.0006
day 1	0.00095	0.00145	0.0014
day 2	0.00553	0.01145	0.01205
day 3	0.0197	0.02245	0.02105
day 4	1.215	1.285	1.3055
day 7	4.18	5.245	5.1525

Source: Own study.
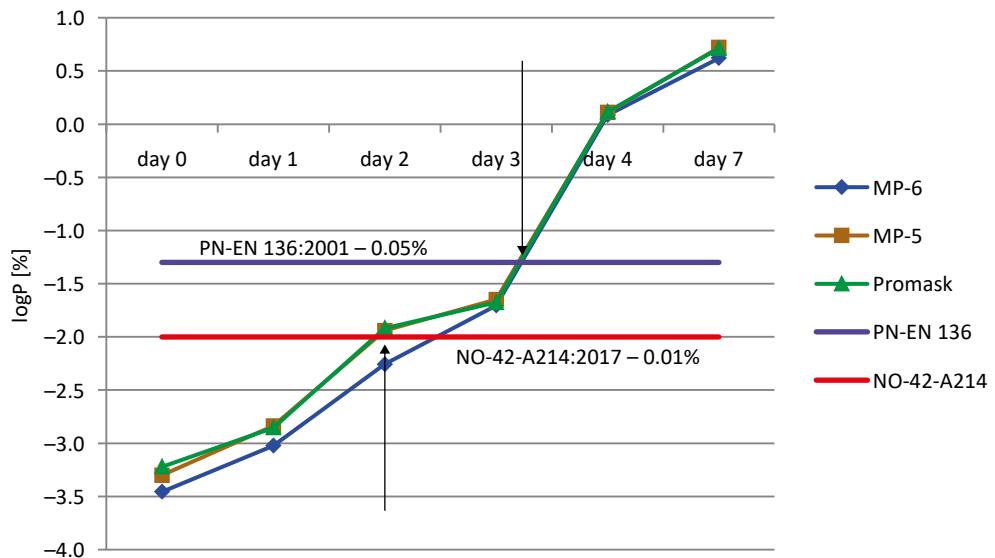
Fig. 10. Results of total inward leakage tests of the mask with 0-7-day facial hair
Source: Own study.

in any document but the combined filters should be replaced with new ones after such tests.

3. In national factory and research laboratories, standardization documents were implemented and appropriate test procedures were developed for the methods for fitting masks under static and dynamic conditions.

In the Polish Armed Forces, the optoelectronic method of mask fitting with the use of PortaCount or other equivalent devices should be widely implemented. It will ensure a standard-compliant level of mask fit.

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Conflict of interests

All authors declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Władysław Harmata ⓘ https://orcid.org/0000-0001-6271-9000
Dorota Kamionek ⓘ https://orcid.org/0000-0002-0208-707X

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Biographical note

Władysław Harmata – Dr. hab. Eng., graduated from the Faculty of Chemistry and Technical Physics of the Military University of Technology in Warsaw in 1978. He is Professor at the Faculty of New Technologies and Chemistry of the Military University of Technology. He specializes in ecology, contamination elimination, and protection against contamination. He is the co-author of 9 national patents and 20 implementations for the Polish Armed Forces. The results of the research were published in about 400 original scientific papers, author of 8 monographs and academic textbooks.

Dorota Kamionek – MSc, graduated in 2008 from the Faculty of New Technologies and Chemistry of the Military University of Technology in Warsaw. Since 2008, she has been working at the Military Institute of Chemistry and Radiometry. Currently, she is the Manager of the Accredited Research Laboratory for Respiratory Protection and acting Head of the Department of Protection against Contamination. She is the author of unique research procedures and test results of individual and collective means of protection against contamination.

Zasady dopasowania filtracyjnych masek przeciwgazowych

STRESZCZENIE	Przedstawiono wyniki badań dopasowania współczesnych masek filtracyjnych z wykorzystaniem metody optoelektronicznej w czasie długotrwałego użytkowania. Poddano je analizie i porównano z wynikami badań metody referencyjnej – całkowitego przecieku wewnętrznego.
SŁOWA KLUCZOWE	ochrona indywidualna, dopasowanie masek filtracyjnych

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