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PERSONAL PROTECTIVE EQUIPMENT FOR RESCUERS INVOLVED IN CBRN INCIDENTS. CASE STUDY FOR SELECTED HAZARD SCENARIOS

ABSTRACT

One of the challenges in modern rescue are terrorist attacks in which use is made of chemical, biological, radiation and nuclear (CBRN) agents. The mass nature of such incidents causes participation in the operations of various services. The first stage of responding to CBRN incidents is often attended by several hundred rescuers. Important factor influencing the speed and effectiveness of actions thus increasing the safety of rescuers is the appropriate selection and optimization of personal protective equipment (PPE). Although the discussion on the selection of PPE during CBRN incidents has been going on for many years, the main emphasis is on solutions used by the military. There is much less work on PPE for rescuers who are usually the first line of defence. The variety of tasks performed by them and a multitude of factors determining the selection of PPE makes it difficult to find a unified approach to this problem. The aims of this paper consist of identification of factors that should be taken into account when selecting PPE for rescuers, reviewing the standards in this area and select the optimal PPE for rescuers during CBRN incidents based on the two the most realistic hazard scenarios. This study contains a critical review of literature and standards in the field of PPE for rescuers, includes outcomes from observation and may be a catalyst for a discussion of this problem.

KEYWORDS

CBRN, rescuers, personal protective equipment (PPE), EU-SENSE, safety of rescue operations

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ŚRODKI OCHRONY INDYWIDUALNEJ DLA RATOWNIKÓW BIORĄCYCH UDZIAŁ W ZDARZENIACH CBRN. STUDIUM PRZYPADKU DLA WYBRANYCH SCENARIUSZY ZAGROŻEŃ

ABSTRAKT

Jednym z wyzwań współczesnego ratownictwa są ataki terrorystyczne z użyciem środków chemicznych, biologicznych, promieniotwórczych i jądrowych (CBRN). Masowy charakter takich zdarzeń powoduje zaangażowanie w działania różnych służb. W pierwszej fazie reagowania na zdarzenia CBRN bierze udział często kilkuset ratowników. Istotnym czynnikiem wpływającym na szybkość i skuteczność działań, a tym samym na zwiększenie bezpieczeństwa ratowników jest odpowiedni dobór i optymalizacja środków ochrony indywidualnej (ŚOI). Choć dyskusja na temat doboru środków ochrony indywidualnej podczas zdarzeń CBRN trwa od wielu lat, główny nacisk kładzie się na rozwiązania stosowane przez wojsko. Znacznie mniej prac poświęconych jest środkom ochrony indywidualnej dla ratowników, którzy stanowią zazwyczaj pierwszą linię obrony. Różnorodność wykonywanych przez nich zadań oraz mnogość czynników determinujących dobór środków ochrony indywidualnej utrudnia znalezienie jednolitego podejścia do tego problemu. Celem pracy jest identyfikacja czynników, które powinny być brane pod uwagę przy doborze środków ochrony indywidualnej dla ratowników, przegląd standardów w tym zakresie oraz wybór optymalnych środków ochrony indywidualnej dla ratowników podczas zdarzeń CBRN w oparciu o dwa najbardziej realistyczne scenariusze zagrożeń. Niniejsze opracowanie zawiera krytyczny przegląd literatury i norm w zakresie środków ochrony indywidualnej dla ratowników, zawiera wyniki obserwacji i może być katalizatorem do dyskusji nad tym problemem.

SŁOWA KLUCZOWE

CBRN, ratownicy, środki ochrony indywidualnej, EU-SENSE, bezpieczeństwo działań ratowniczych

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INTRODUCTION

The current world is evolving on many levels, also in terms of hazards to humanity[1,2]. The availability of chemical substances on the market, access to laboratories that allows modifying pathogens, the broad use of radioactive isotopes in medicine and industry, as well as international trade caused that the use of chemical, biological, radiological or nuclear (CBRN) agents in terrorist attacks is one of the most important threats faced by the world today[3,4].

1 M. Tryboń, I. Grabowska-Lepczak, M. Kwiatkowski, *Bezpieczeństwo człowieka w obliczu zagrożeń XXI wieku*, „Zeszyty Naukowe SGSP" 2011, Vol. 41.

2 Cz. Marcinkowski, *Zagrożenia i wyzwania transgranicznego bezpieczeństwa współczesnego świata*, „Doctrina. Studia społeczno-polityczne" 2011, Vol. 8.

3 B.B. Fyanka, *Chemical, biological, radiological and nuclear (CBRN) terrorism: Rethinking Nigeria's counterterrorism strategy*, "African Security Review" 2020, Vol. 28, Issue 3–4.

4 F. Benolli, M. Guidotti, F. Bisogni, *The CBRN Threat. Perspective of an Interagency Response* [in:] G. Jacobs, I. Suojanen, K. Horton, P. Bayerl (eds), *International Security Management. Advanced Sciences and Technologies for Security Applications*, "Springer, Cham." 2021.

The main objectives of attacks with the use of CBRN agents, commonly known as acts of "super-terrorism", are destabilization of the state internal security system and political blackmail. An important feature of CBRN incidents is the mass-scale impact on people, the environment and infrastructure. Potential consequences of CBRN incidents depend, *inter alia*, on the type of agent used, its amount and concentration, dispersion method, weather conditions and the place of the incident. In order to maximize the range of the attack, in addition to CBRN agents, terrorists most often use explosives (dirty bombs, trap cars), technical means such as compressed aerosols, unmanned aerial vehicles and/or contaminated live organisms. CBRN incidents usually cause difficulties in determining their starting moment and identifying the agent used. Taking into account the multidimensional nature of CBRN attacks (the use of several agents at the same time, simultaneous attacks in several places, etc.), they require the involvement of significant amounts of forces and resources of various entities, including secret intelligence service, rescue services (fire service, police, ambulance), armed forces and public administration bodies responsible for crisis management. While the intelligence services and state administration bodies mainly perform tasks in the field of prevention, early detection of planned attacks and recovery after the occurrence of CBRN hazards, emergency services are the first line of response[5,6].

Although the use of chemical, biological and radiological agents for non-military purposes began in the 1950s, March 20, 1995 is a special date to start considering CBRN hazards. On that day, the Aum Shinrikyō religious sect atomized a poisonous warfare agent, sarin, on a Tokyo metro train. As a result of the attack, 12 people died and over 5,000 were injured. Emergency services responding to an incident were not adequately prepared. They lacked knowledge and equipment and were consequently exposed to the poisonous chemical. As a result, 135 members of the rescue teams involved

5 R. Thornton, B. Court, J. Meara, V. Murray, I. Palmer, R. Scott, M. Wale, D. Wright, *Chemical, biological, radiological and nuclear terrorism: an introduction for occupational physicians*, "Occupational Medicine" 2004, Vol. 54, Issue 2.

6 A. Malizia, *Disaster management in case of CBRNe events: an innovative methodology to improve the safety knowledge of advisors and first responders*, "Defense & Security Analysis" 2016, Vol. 32, Issue 1.

in the rescue operation were afflicted. Many people for some time after the attack suffered from illnesses resulting from being in a zone contaminated with sarin, including difficulty in breathing and brain damage and/or depression[7,8]. This data is considered by many as a starting point to initiate work on the international forum to improve preparedness and resilience to CBRN incidents[9,10]. One of the examples of the above-mentioned activities are international projects financed by the EU, including SLAM (Standardization of laboratory analytical methods)[11], SE-CBRN-URE (Support for European Union action in the field of CBRN security managers education)[12], Mall-CBRN (Creation of CBRNE protection system for large area shopping malls)[13], eNotice (European Network of CBRN Training Centers)[14], EDEN (End-user Driven Demo for CBRNe)[15] or project EU-SENSE (European Sensor System for CBRN Applications)[16]. The aim of these projects was/is to strengthen the cooperation of services, improve skills, and develop, test and implement modern solutions for the detection of CBRN agents and remote measurement of contamination.

Experience gained from the attacks so far and observations made on the basis of the above mentioned projects indicate that one of the current and serious challenges of CBRN incidents is to optimise solutions in the field of personal protective equipment (PPE) for rescuers (firefighters, policemen,

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7 T. Okumura, K. Suzuki, A. Fukuda, A. Kohama, N. Takasu, S. Ishimatsu, S. Hinohara, *The Tokyo subwaysarin attack: disaster management. Part 1: community emergency response*, "Academic Emergency Medicine" 1998, Vol. 5, Issue 6.

8 Y. Nishiwaki, K. Maekawa, Y. Ogawa, N. Asukai, M. Minami, K. Omae, *Effects of sarin on the nervous system in rescuer staff members and police officers 3 years after the Tokyo subway sarin attack*, "Environmental Health Perspectives" 2001, Vol. 109, Issue 11.

9 R. Thornton, et al., *op. cit.*

10 Y. Asai, J.L. Arnold, *Terrorism in Japan*, „Prehospital and Disaster Medicine" 2003, Vol. 18, Issue 2.

11 Electronic source: https://cordis.europa.eu/project/id/285410/reporting (accessed on 15.03.2021).

12 Electronic source: http://secbrnure.uni.lodz.pl/ (accessed on 15.03.2021).

13 Electronic source: http://mall-cbrn.uni.lodz.pl/?page_id=15 (accessed on 15.03.2021).

14 Electronic source: https://www.h2020-enotice.eu/ (accessed on 15.03.2021).

15 Electronic source: https://eden-security-fp7.eu/ (accessed on 15.03.2021).

16 Electronic source: https://eu-sense.eu/ (accessed on 15.03.2021).

medics)[17,18,19,20]. Publications on this subject focus mainly on PPE used by the military. However, due to the different nature of the tasks of both services, they are not always optimal for rescuers[21,22,23].

The aims of this paper are: identification of factors that should be taken into account when selecting PPE for rescuers, reviewing the standards in this area both in the Polish and international arena and as a consequence the selection of optimal PPE for rescuers during CBRN incidents based on the two hazard scenarios, i.e. spraying of sarin during a mass event and the release of ammonia during transport. The choice of substances was based on a literature query[24,25] which indicates that both sarin and ammonia, due to their wide range of action and potential easy access, are characterized by a high probability of use.

1. MATERIAL AND METHODS

In order to achieve the assumed aims, the authors used the following research methods:

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17 L. Simeonova, C. Hylak, *Personal protective equipment (PPE) in CBRN incidents*, "The Science For Population Protection" 2015, Vol. 1.

18 A. Calder, S. Bland, *CBRN considerations in a major incident*, "Surgery" (Oxford) 2018, Vol. 36, Issue 8.

19 S. Razak, S. Hignett, J. Barnes, *Emergency Department Response to Chemical, Biological, Radiological, Nuclear, and Explosive Events: A Systematic Review*, "Prehospital and Disaster Medicine" 2018, Vol. 33, Issue 5.

20 A. Trzos, K. Łyziński, K. Jurkowski, *Emergency Medical Services in CBRNE/HAZMAT Incidents*, "Safety and Fire Technology" 2019, Vol. 54, Issue 2.

21 Z. Zielonka, R. Pich, *Najnowsze indywidualne środki ochrony przed skażeniami stosowane w PKW*, „Zeszyty Naukowe WSOWL" 2008, Vol. 2, Issue 148.

22 P. Maciejewski, W. Robak, M. Młynarczyk, *Protection from CBRN Contamination in the Polish Armed Forces*, "BITP. Bezpieczeństwo i Technika Pożarnicza" 2015, Vol. 37, Issue 1.

23 W. Harmata, M. Witczak, *Defence against weapons of mass destruction: technical and functional solutions in personal protection for Territorial Defence Forces*, "Biuletyn Wojskowej Akademii Technicznej" 2018a, Vol. 67, Issue 2.

24 J.A. Chalela, W.T. Burnett, *Chemical Terrorism for the Intensivist*, "Military Medicine" 2012, Vol. 177, Issue 5.

25 W. Harmata, M. Witczak, *Diagnosis of Contamination in Poland – Current State of Knowledge*, "Research and Development" 2018b, Vol. 52, Issue 4.

1) literature analysis – review of the literature sources as well as domestic and foreign procedures for dealing with CBRN hazards
   - identification of factors that should be taken into account when selecting PPE at the time of CBRN incidents;
   - presentation of the main principles governing the selection of PPE during CBRN incidents;
2) observations – direct observation of the way of responding to CBRN hazards of the state fire service during the measurement tests of the EU-SENSE system organized at the Base Training and Rescue Innovation Centre of the Main School of Fire Service in Nowy Dwór Mazowiecki (August 2020, June 2021) and during exercises in case of two CBRN hazard scenarios, i.e. the release of sarin during a mass event and an accident involving a tanker transporting ammonia[26]
   - definition of rescue tasks performed during CBRN incidents requiring the use of highly resistant PPE,
   - proposing personal protective equipment for rescuers in the event of CBRN hazards, broken down taking into account different risk zones.

2. RESULTS AND DISCUSSION

2.1. Factors determining the selection of personal protective equipment during CBRN incidents

Personal Protective Equipment comprises all manufactured products to be worn and owned by the user, ensuring protection against all threats to life, health and safety. It can therefore be concluded that PPE is designed to protect workers from serious workplace injuries or illnesses resulting from contact with chemical, radiological, physical, electrical, mechanical, or other workplace hazards[27]. Besides face shields, safety glasses, hard hats, and safety shoes, protective equipment includes a variety of devices and garments such

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26 The works described in the manuscript were carried out in 2018–2021 at the Main School of Fire Service. They were part of the EU-SENSE project financed from the research and innovation program of the European Union Horizon 2020 under the grant agreement No. 787031.

27 Occupational Safety and Health Administration, Personal Protective equipment, OSHA 3151-12R, 2004.

as goggles, coveralls, gloves, vests, earplugs, and respirators[28]. The above measures should be used in conjunction with other protective measures, such as exposure assessment, risk development simulations, situational awareness systems or measuring equipment. In general, the PPE is divided into two major groups[29]:

- Respiratory protective equipment – the essential part of basic protection, which is divided into two types: air-purifying respirators, in which the atmospheric air is cleaned or filtered before reaching the user, and the self-contained breathing apparatus (SCBA), which provides the user with clean air regardless of the surrounding atmosphere.
- Body surface protective equipment – protective clothing, designed to protect the skin. The type of protective clothing depends mainly on the level of contamination and the nature of the tasks performed.

The main tasks of rescuers during CBRN incidents are[30,31]:

- hazard recognition and identification,
- securing the scene of the event and designating the danger zone,
- catching of the perpetrator,
- evacuation of injured and endangered people and animals out of the danger zone, warning and alerting about the threat and suggesting rules of behaviour,
- carrying out measurements with the use of available instruments, limiting the leakage of petroleum substances, sampling,
- putting up water curtains,
- conducting initial decontamination of people on the border of the danger zone,
- qualified first aid,
- performing other activities, according to the equipment and own knowledge in a given field.

Almost all of the above tasks require the use of highly resistant PPE. PPE is selected by commanders of operations or other security officers on the scene. The type of PPE required depends mainly on the type of agent used

28 *Ibid.*
29 L. Simeonova, et al., *op.cit.*
30 R. Thornton, et al., *op. cit.*
31 A. Malizia, *op. cit.*

(chemical, biological, radiological, and nuclear). The main factors to consider during selecting PPE when using chemical warfare agents are[32]:

- Type of hazardous substance,
- Amount of oxygen in the air,
- Concentration of chemical agent and explosive concentrations,
- Type of contamination (e.g. water-based mists, aerosols, gas, steam, vapours, dispersed liquid aerosol).

The following factors should be considered when selecting a PPE when biological warfare agents were used[33]:

- Survivability/stability of pathogen in environment,
- Sensitivity to disinfection substances,
- Probable dissemination method,
- Infectious dose,
- Incubation period,
- Mortality and prevalence,
- Communicability of disease,
- Availability of vaccines and/or antibiotics.

When selecting PPE during radiation incidents, the following factors should be taken into account[34]:

- Type of radioactive substance,
- Type of radiation,
- Radiation dose,
- Distance from the source,
- Means of release (e.g. dirty bomb generating other hazards).

In addition, other factors to consider when selecting PPE during CBRN incidents, regardless of the type of agent used, are: the nature of the tasks performed by rescuers, working conditions, including ambient temperature,

32 K. Jóźwik, M. Ceremuga, A. Tchórzewski, *Individual protection equipment* [in:] B. Koźniewska (ed.), *CBRN Security Manager Handbook*, Łódź University Press, Łódź 2018.

33 A. Michalski, M. Kwiatek, A. Mełgieś, J. Joniec-Wiechetek, K. Lasocki, *Personal protective measures* [in:] B. Koźniewska (ed.), *CBRN Security Manager Handbook*, Łódź University Press, Łódź 2018.

34 P. Furtak, M. Ceremuga, J. Siczek, *Radiation and defense against nuclear weapons* [in:] B. Koźniewska (ed.), *CBRN Security Manager Handbook*, Łódź University Press, Łódź 2018.

humidity and visibility, the time of substance penetration through the material, the length of time a rescuer can wear a certain combination of equipment and the rescuer's physical condition (physical fitness, mental endurance, practice). The use of PPE should not limit the mobility and dexterity of rescuers, and it should not be an obstacle to communication[35,36]. Each time when deciding on the selection of PPE, the risk that a hazardous substance could be released should be taken into account. This type of assessment is a safety and health assessment as many substances are highly toxic to both the skin and the respiratory tract. Exposure factors, i.e. odour, smoke, or fumes may not be felt or present. In such cases, exposure monitoring is difficult. Based on the properties of the hazardous substances used in past CBRN attacks and the site conditions, the response commander needs to implement appropriate emergency actions, including selecting appropriate PPE for responders[37,38].

As regards CBRN incidents, even in areas that are not considered to pose a risk, there may be a possibility of a minimal level of transient or unknown exposures following an incident. In this regard, good practices should be applied, such as informing people about the location of the incident and control spheres, providing information on signs and symptoms of exposure, providing a method of reporting suspected exposure, suggesting attention to general hygiene practices and providing information on the voluntary use of PPE. The division of the incident area into zones makes risk management easier, and as an effect the appropriate organization of activities, personnel management and the use of logistic resources, including individual means of protection against contamination. According to the standards developed by the Occupational Safety and Health Administration (OSHA), the affected area should be divided into three zones[39]:

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35 L. Simeonova, et al., *op. cit.*

36 A. Trzos, et al., *op. cit.*

37 Regulation of the Minister of Internal Affairs and Administration of 16 September 2008 on detailed conditions of occupational safety and health for the service of firefighters of the National Fire Service (Polish Journal of Laws/Dz.U. 2008 no. 180 item 1115).

38 Państwowa Straż Pożarna, Zasady organizacji ratownictwa chemicznego i ekologicznego w Krajowym Systemie Ratowniczo Gaśniczym, Warsaw, November 2021.

39 Electronic source: https://www.osha.gov/emergency-preparedness/cbrn-matrix#home (accessed on 25.08.2021).

- hot zone (red zone) – areas where there is evidence of significant chemical, biological, radiological or nuclear (CBRN) contamination or where there is a strong suspicion but the agent has not been characterized. This area is believed to be life-threatening through both skin contact and inhalation. The most advanced PPE is generally needed in case of an active release still taking place or when the release has stopped, but there is no information on the duration of the release or the concentrations of CBRN agents in the air. Until monitoring results permit other decisions to be made for rescuers going to a release area where CBRN is suspected, self-contained breathing apparatus should be used and skin protection should be a 100% hermetic hypertensive protective suit. The exposure time should be minimized to the time necessary to save life or for initial monitoring. In this zone, it is necessary to avoid unnecessary contact with surfaces or potentially contaminated material, use natural ventilation flows to reduce exposure; after leaving the zone, the PPE should be disinfected and the condition of rescuers in terms of signs and symptoms of exposure need to be assessed;
- warm zone (yellow zone) – areas where contamination with chemical, biological, radiological or nuclear agents is possible, but where active release is complete and initial monitoring is in place. For this zone, consideration should be given to areas in close proximity to the release area or which are known to be contaminated, as well as certain work activities in the periphery of the incident area. Risk factors to consider include the determination of the relative risk for occupational inhalation activities based on available air monitoring results, skin contact and absorption potential, proximity to an incident scene and wind directions;
- cold zone (green zone) – areas where contamination with chemical, biological, radiological or nuclear factors is unlikely. This zone covers the area beyond the expected significant spread of the initial event and the extent of recontamination from traffic and emergency services.

2.2. Rules for the selection of personal protective equipment

Due to the different nature of tasks carried out by the military and rescuers, different standards have been defined by international institutions, e.g. Occupational Safety and Health Administration (OSHA), Environment Protection Agency (EPA), or the National Fire Protection Association

(NFPA)[40,41] for equipping these services with PPE. In this paper, attention is paid mainly to PPE intended for rescuers. According to international regulations, combinations or sets of PPE for civil services (which should be understood as rescuers) have been divided according to the classifications presented in Tables 1 and 2.

Table 1. Personal protection equipment classification system for emergency responders according to the standards set by the Occupational Safety and Health Administration (OSHA) and the Environment Protection Agency (EPA)[42]

OSHA/EPA Classification	Level A	Level B	Level C	Level D
Protection provided	Highest level of skin, eye and respiratory protection	Highest level of respiratory protection; lower level of skin protection	Lower level of respiratory and skin protection. Adequate for radiation event response where other hazards have been determined not to be present.	Lowest level of respiratory and skin protection.
Indications	Identified or suspected hazards requir-ing maximal skin, eye, and respiratory protection.	Identified or suspected hazards requir-ing maximal respiratory protection..	Hazards have been identified. Hazards will not be ab-sorbed by or adversely affect exposed skin.	Atmosphere contains no known hazards.

40 National Institute for Occupational Safety and Health, Guidance on Emergency Responder Personal Protective Equipment (PPE) for Response to CBRN Terrorism Incidents. Publication No. 2008–132, NIOSH, 2008, pp. 5.

41 L. Simeonova, et al., *op. cit.*

42 J.L. Hick, D. Hanfling, J.L. Burstein, J. Markham, A.G. Macintyre, J.A. Barbera, *Sprzęt ochronny dla personelu odkażającego placówki służby zdrowia: przepisy, zagrożenia i zalecenia*, "Annals of Emergency Medicine" 2003, Vol. 42, Issue 3.

cont. Table 1.

OSHA/EPA Classification	Level A	Level B	Level C	Level D
Indications	Working in confined areas where hazards have not been fully characterized.	Working in atmospheres containing less than 19.5% oxygen. Lower level skin hazard may be present.	All criteria for using an air purifying respirator are met (i.e., concentrations of all airborne contaminants are known, appropriate filters are available, oxygen levels are sufficient).	No or very low potential for unexpected respiratory or skin contact with environmental hazards.
Who should wear it	First responders When there is an identified or potential risk of biological, liquid or vapour chemical hazard exposure.	First responders When entering the most heavily contaminated radiation zones to rescue victims or protect valuable property necessary for public welfare	First responders and first receivers When caring for patients/victims likely to be contaminated with radiological material	First receivers When working in post-decontamination areas Standard Precautions PPE (per protocol) should be worn for infection control purposes[1]

[1] Standard precautions PPE and procedures used to prevent transmission of infections within healthcare settings provides adequate protection against low levels of radiological contamination that may be found in post-decontamination areas of the hospital (e.g., emergency department and surgical suites). No formal PPE is required to be worn when delivering care to persons with high dose radiation exposure although reverse isolation procedures will need to be observed as neutropenia becomes prominent.

Table 2. Classes of protective sets for first responders defined by the National Fire Protection Association (NFPA)[43]

NFPA Protective Ensemble Class	Level of Skin Protection	Level of Respiratory Protection	Notes Concerning Use
Class 1 (most protective)	Protective ensemble totally encapsulates wearer and respiratory protective equipment	Mandatory use of NIOSH-certified CBRN self-contained breathing apparatus (SCBA)	Establishes minimum level of protection for first responders against: Toxic vapours, liquids, and particulates during hazardous materials incidents Specific chemical and biological terrorism agents in vapour, liquid-splash, and particulate environments during CBRN terrorism incidents.
Class 2		Requires the use of NIOSH-certified CBRN self-contained breathing apparatus (SCBA)	For use in terrorism incidents involving vapour or liquid chemical or particulate hazards where concentrations are at or above levels immediately dangerous to life or health
Class 3		Requires the use of NIOSH-certified CBRN air-purifying respirators (APRs) or NIOSH-certified CBRN powered air-purifying respirators (PAPRs)	For use in terrorism incidents involving low levels of vapour or liquid chemical hazards where concentrations are below levels immediately dangerous to life or health

43 NIOSH, *op. cit.*

cont. Table 2.

NFPA Protective Ensemble Class	Level of Skin Protection	Level of Respiratory Protection	Notes Concerning Use
Class 4 (least protective)	Ensembles not tested for protection against chemical vapour or liquid permeability, gas-tightness, liquid integrity	Permits the use of NIOSH-certified CBRN air-purifying respirators (APRs) or NIOSH-certified CBRN powered air-purifying respirators (PAPRs)	For use in terrorism incidents involving biological or radiological particulate hazards only where the concentrations are below levels immediately dangerous to life or health

Source:

In Poland, the National Firefighting and Rescue System (KSRG) is established to respond to incidents involving CBRN materials[44,45]. The occupational safety and health conditions of the service of firefighters and rescuers participating in rescue operations, taking into account the requirements for personal protective equipment, are set out in the Regulation of the Minister of Internal Affairs and Administration of August 31, 2021 on the detailed occupational safety and health conditions of the firefighters service of the State Fire Service (Dz.U.2021.1681)[46], according to which the commander ensures the use of PPE. This regulation does not specify what kind of measures these need to be. According to other regulations, they must meet the conditions set out in the Act of August 30, 2002 on the conformity assessment system[47] and in the Regulation of the European Parliament and of the Council (EU) of 9 March 2016 on personal protective equipment and repealing Council

44 Act of 24 August 1991 on fire protection (Polish Journal of Laws/Dz.U. 1991 No. 81 item 351).

45 Regulation of the Minister of Internal Affairs and Administration of 3 July 2017 on the detailed organisation of the national rescue and firefighting system (Polish Journal of Laws/Dz.U. 2017, item 1319).

46 (Polish Journal of Laws/Dz.U. 2021, poz.1681), *op. cit.*

47 Act of 30 August 2002 on the conformity assessment system (Polish Journal of Laws/Dz.U. 2002 No. 166 item 1360).

Directive 89/686/EEC ((EU) 2016/425)[48]. Another important document relating to the issue of assuring the safety of rescuers during CBRN incidents are the Rules for the organization of chemical and ecological rescue in the National Fire and Rescue System of November 2021[49], which define the minimum standards of equipment in the event of incidents requiring chemical, ecological and radiation rescue (e.g. the required amount in a vehicle emergency clothes, breathing apparatus, gauges of a certain type, etc.). This document does not specify strict rules for the use of this equipment in particular zones or different states of hazard. According to the aforementioned principles, chemical rescue has two scopes: the basic one and the specialized one. The basic scope covers rescue activities performed by all rescue and firefighting units of the State Fire Service, as well as other fire protection units or other entities declaring operational readiness to perform these tasks according to their organizational and equipment capabilities and the level of training. The priority of the organization of chemical and ecological rescue activities in the basic scope is always saving life and health. Already at the basic level, the State Fire Service should be equipped with appropriate personal protective equipment that will protect the rescuer against contaminated, infected, irradiated or poisoned material, and again there are no recommendations as to the types of PPE that should be used in individual zones. Measuring instruments are also important as they contribute to a more accurate risk assessment of a hazard, including its source and concentrations of hazardous substances.

2.3. SELECTION OF PPE BASED ON TWO HAZARD SCENARIOS

2.3.1. SCENARIO 1.

The subject of an analysis of the first scenario is a potential situation where there ammonia is deliberately released during transport. Ammonia is broadly used in the chemical industry, as an intermediate product for the production of other substances, for the production of fertilizers, ammonia water, explo-

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48 Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC (Text with EEA relevance).

49 PSP, *op. cit.*

sives, for the saponification of fats and oils, as a cooling agent in refrigeration equipment, in the pharmaceutical industry, in electronics for etching printed circuits and in metallurgy[50]. It is one of the most dangerous substances with a sharp and penetrating odour[51]. The risk of a hazard to the population occurs mainly during the unsealing of the ammonia-containing tank and the emission of gases into the atmosphere or in the event of leakage of liquid ammonia and its spreading. The following symptoms are associated with ammonia poisoning: convulsions, coma and cell death in the central nervous system. Contact with this compound may occur through the mucous membranes, skin and respiratory system. Table 3 presents the Acute Exposure Guideline Levels (AEGLs) of ammonia, while Table 4 presents the properties of ammonia, hazard identification and the personal protective equipment necessary for use by rescuers in individual hazard zones.

Table 3. Ammonia Acute Exposure Guideline Levels (AEGL)

AEGLs	10 min	30 min	60 min	4 h	8 h
AEGL 1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure (Unit: ppm)	30	30	30	30	30
AEGL 2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape (Unit: ppm)	220	220	160	110	110
AEGL 3: Life-threatening health effects or death (Unit: ppm)	2.700	1.600	1.100	550	390

50 G. Rogalewicz, W.M. Bajdur, *Modelowanie zagrożeń przemysłowych na przykładzie substancji chemicznej – amoniaku*, "Technika, Informatyka, Inżynieria Bezpieczeństwa" 2014, Vol. 2.

51 Electronic source: https://pubchem.ncbi.nlm.nih.gov/source/EPA%20Acute%20Exposure%20Guideline%20Levels%20 (accessed on 23.08.2021).

Table 4. Properties of ammonia and the selection of personal protective equipment with division into hazard zones

Scenario	Properties and identification of hazards	Personal protective equipment
Scenario 1 Ammonia	Molecular formula: NH_3 CAS number: 7664-41-7 Information on basic physical and chemical properties: • Molecular weight: 17.031 • Physical state at 20°C: gas • Colour: colourless gas • Odour: sharp, cloying, repellent • Melting point (1013 hPa): –77,7°C • Boiling point (1013 hPa): –33,35°C • Flash point: not applicable • Temperature of self--ignition: 630°C • Explosion limits in a mixture with air: – lower: 15% vol. – upper: 28% vol. • Explosion limits in a mixture with oxygen: – lower: 14% vol. – upper: 79% vol. • Stoichiometric concentration: 21.87% vol. • Minimum ignition energy in the air: 680 mJ	RED ZONE This zone requires the highest level of protection for the skin, respiratory system and eyes. This is the maximum protection for workers at risk of exposure to unknown chemical hazards or levels above IDLH* or greater than AEGL-2. Respiratory protection: NIOSH-certified full-face CBRN breathing apparatus, operating in pressure-demand or pressure-demand mode; respirator with an air hose with an additional escape bottle; completely hermetic suit (TECP) providing protection against CBRN agents. Hand protection: Chemical resistant gloves (exterior). Chemical resistant gloves (inside). Skin and body protection: Chemical-resistant boots with steel toe and upper. Coverall, long underwear and a helmet worn under the TECP coverall are optional items. YELLOW ZONE When the contamination and concentration of the contaminant are known and respiratory protection criteria are met when using

cont. Table 4.

Scenario	Properties and identification of hazards	Personal protective equipment
Scenario 1 Ammonia	• Gas density (0°C, 1013 hPa): 0.771 g/dml • Liquid density (–33.43°C, 1013 hPa): 0.682 g/cm^3 • Vapour density relative to air (0°C, 1013 hPa): 0.597 • Gas pressure (20°C): 0.8 MPa • Saturated vapour concentration: not applicable, gas • Water solubility (20°C, 1013 hPa): 42.8% wt. • Solubility in other solvents: – absolute ethanol (0°C, 1013 hPa): 20.95% wt.	air-purifying respirators (APR) or powered air-purifying respirators (PAPR). This level is appropriate for patient/victim decontamination. Tightly matched NIOSH CBRN certified APR with canister type gas mask or CBRN PAPR for air levels higher than AEGL-2. Respiratory protection: NIOSH-certified CBRN PAPR with a loose fitting face piece, hood or helmet and filter or a cartridge/filter combination of organic vapour, acid gas and particulate matter or continuous flow respirator for air levels higher than AEGL-1. Chemical resistant coverall with hood that provides CBRN protection. Hand protection: Chemical resistant gloves (exterior). Chemical resistant gloves (inside). Skin and body protection: Chemical-resistant boots with steel toe and upper. Escape mask, face shield, coveralls, long underwear, helmet worn under the chemical resistant suit, and chemically resistant

cont. Table 4.

Scenario	Properties and identification of hazards	Personal protective equipment
Scenario 1 Ammonia		disposable shoe covers worn over the chemical resistant suit are optional items. Escape mask, face shield, coveralls, long underwear, helmet worn under the chemical resistant suit, and chemically resistant disposable shoe covers worn over the chemical resistant suit are optional items. GREEN ZONE When the pollutant and its concentration are known and the concentration remains below the relevant occupational exposure limit or less than AEGL-1 for the duration given. Suits or other workwear, shoes and gloves will be sufficient.

IDELH – Immediately Dangerous To Life or Health
Source: own study based on[52]

2.3.2. SCENARIO 2

The subject of the analysis of the second scenario is the potential situation in which sarin was used during a mass event. Sarin appears as a colourless, odourless liquid, with practically no odour in pure state and is used as a quick-acting military chemical nerve agent. It is one of the chemical warfare agents. Due to its high volatility, it can easily be converted from liquid to a gaseous form. Sarin synthesis comprises the esterification of methylphosphonic difluoride with isopropanol in the presence of isopropylamine, which

52 Electronic source: https://pubchem.ncbi.nlm.nih.gov/compound/222#section=Personal-Protective-Equipment-(PPE) (accessed on 25.08.2021).

acts as a basic catalyst and a substance neutralizing the formed hydrogen fluoride. The mechanism is based on the irreversible blocking of the action of acetylcholinesterase, i.e. an enzyme that breaks down acetylcholine by creating a covalent bond between the inhibitor's phosphorus atom and the enzyme's esterase centre, and then phosphorylation of the serine group. Inhibition of the action of acetylcholinesterase causes the accumulation of significant amounts of acetylcholine in the synaptic gaps and neuromuscular plates[53]. This results in stimulation of nicotinic and muscarinic receptors, which is referred to as "cholinergic breakthrough". The stimulation of muscarinic receptors causes constriction of the pupils and lack of response to light, hypersalivation and tearing, vomiting, diarrhoea, dyspnoea, pulmonary oedema and bradycardia. The stimulation of nicotinic receptors, on the other hand, causes muscle weakness, nystagmus, and fibrillary tremors. Additional symptoms of poisoning also include speech disorders, anxiety, and difficulty concentrating. Extremely toxic lethal dose in humans can be as low as 0.01 mg/kg. Sarin is an extremely active cholinesterase inhibitor. Death occurs within 15 minutes after absorption of its lethal dose. Table 5 presents sarin Acute Exposure Guideline Levels, while table 6 presents the properties of sarin, identifies hazards and presents personal protective equipment necessary for use by rescuers in individual hazard zones.

Table 5. Sarin Acute Exposure Guideline Levels (AEGLs)[54]

AEGLs	10 min	30 min	60 min	4 h	8 h
AEGL 1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure (Unit: ppm [mg/m^3])	0.0012 [0.0069]	0.00068 [0.0040]	0.00048 [0.0028]	0.00024 [0.0014]	0.00017 [0.0010]

53 P.R. Chai, E.W. Boyer, H. Al-Nahhas, T.B. Erickson, *Toxic chemical weapons of association and warfare: nerve agents VX and sarin*, "Toxicology Communication" 2017, Vol. 1, Issue 1.

54 Electronic source: https://pubchem.ncbi.nlm.nih.gov/source/EPA%20Acute%20Exposure%20Guideline%20Levels%20 (accessed on 23.08.2021).

cont. Table 5.

AEGLs	10 min	30 min	60 min	4 h	8 h
AEGL 2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape (Unit: ppm [mg/m^3])	0.015 [0.087]	0.0085 [0.050]	0.0060 [0.035]	0.0029 [0.017]	0.0022 [0.013]
AEGL 3: Life-threatening health effects or death (Unit: ppm [mg/m^3])	0.064 [0.38]	0.032 [0.19]	0.022 [0.13]	0.012 [0.070]	0.0087 [0.051]

Source:

Table 6. Properties of sarin and the selection of personal protective equipment with division into hazard zones

Scenario	Properties and identification of hazards	Personal protective equipment
Scenario 2 **Sarin**	Molecular formula: $C_4H_{10}FO_2P$ CAS number: 107-44-8 Information on basic physical and chemical properties: • Molecular weight: 140.11 • Colour: colourless • Odour: almost odourless when pure • Melting point (1013 hPa): –77.7°C • Boiling point (1013 hPa): 147°C at 760 mmHg • Flash point: non-flammable • Density: 1.0887 g/ml in 25°C • Vapour density relative to air (0°C, 1013 hPa): 4.86 (air = 1)	RED ZONE When the highest level of skin, respiratory and eye protection is required. This is the maximum protection for workers at risk of exposure to unknown chemical hazards or levels above IDLH or greater than AEGL-2. **Respiratory protection:** NIOSH-certified full-face SCBA, operating in operating in pressure-demand or pressure-demand mode; respirator with an air hose with an additional escape bottle; completely hermetic suit (TECP) providing protection against CBRN agents.

cont. Table 6.

Scenario	Properties and identification of hazards	Personal protective equipment
Scenario 2 **Sarin**	• Steam pressure: 2.86 mm Hg in 25°C • Water solubility: Miscible with water /1X10+6 mg/L in 25°C /	**Hand protection:** Chemical resistant gloves (exterior). Chemical resistant gloves (inside). **Skin and body protection:** Chemical-resistant boots with steel toe and upper. Coverall, long underwear and a helmet worn under the TECP coverall are optional items. YELLOW ZONE When the contamination and concentration of the contaminant are known and respiratory protection criteria are met when using air-purifying respirators (APR) or powered air-purifying respirators (PAPR). This level is appropriate for patient/victim decontamination. **Respiratory protection:** Tightly matched NIOSH certified APR with canister type gas mask or CBRN PAPR for air levels higher than AEGL-2. NIOSH certified CBRN PAPR with a loose fitting face piece, hood or helmet and filter or cartridge/filter combination with organic vapour, acid gas and particulate matter or continuous flow respirator for air levels higher than AEGL-1.

cont. Table 6.

Scenario	Properties and identification of hazards	Personal protective equipment
Scenario 2 **Sarin**		Chemical resistant coverall with hood that provides CBRN protection. **Hand protection:** Chemical resistant gloves (exterior). Chemical resistant gloves (inside). Skin and body protection: Chemical-resistant boots with steel toe and upper. Escape mask, face shield, coverall, long underwear, helmet worn under chemical protection suit. GREEN ZONE When the pollutant and its concentration are known and the concentration remains below the relevant occupational exposure limit or less than AEGL-1 for the duration given. Limited to coveralls or other workwear, boots and gloves.

Source: own study based on[55]

3. CONCLUSIONS

The conducted reviews of literature sources and relevant standards in the field of personal protective equipment, observations made during exercises of the state fire service[56], conclusions devised during the implementation of

55 Electronic source: https://www.cdc.gov/niosh/ershdb/emergencyresponsecard_29750013.html (accessed on 09.08.2021).

56 The tests were conducted as part of the EU-SENSE project at the Base Training and Rescue Innovation Center of the Main School of Fire Service in Nowy Dwór Mazowiecki (August 2020, June 2021).

the EU-SENSE project and the analysis of two CBRN event scenarios have shown that proposing a unified approach to the selection of PPE for rescuers participating in CBRN incidents still remains a challenge. Due to the diverse nature of the tasks, it is difficult to define PPE that would be optimal for firefighters, paramedics and policemen, therefore each rescue service should develop its own standards based on knowledge and experience and needs connected with the zones in which they carry out operations. In this study, it was possible to do it mainly on the basis of tasks performed by firefighters. However, the multitude of standards in this area, different nature and course of events (using several agents at the same time), and the wide availability of more and more advanced solutions on the market mean that proposing specific PPE models for individual zones is somewhat of a challenge.

The studied exercises confirmed that the selection of PPE should be made subjectively by rescuers, based on their knowledge, experience, good practices and assessment of the situation. Common sense and financial possibilities are also an extremely important factor in this regard. The most important thing is that the measures used meet the standards set for each risk level and ensure the safety of rescuers. Currently available PPE enables operation in the most hazardous zones (red/hot and yellow/cool). They both increase the safety of rescuers, as well as improve the effectiveness of activities, increasing the chances of survival of affected victims present in those zones. Protective clothing allows personnel to work in an area with removable contamination and to exit the area without spreading contamination onto uncontrolled areas, as well as to minimize the adverse effects of chemicals, biological agents, and radiological particulates. However, the use of protective clothing alone will not guarantee complete elimination of contamination of personnel. Currently, no single personal protective equipment can protect the user from exposure to all hazards. It is very important to use additional measuring equipment or systems that improve situational awareness. The answer to these needs may be the EU-SENSE system developed under the project of the same name. The system is based on a novel chemical sensor network consisting of heterogeneous sensor nodes supported by state-of-the-art machine learning and dispersion modelling. Having such a tool in place during CBRN incidents can contribute to better situational awareness by modelling the dispersion of hazardous substances. For a rescuer or action commander, this is a big step forward in terms of the ability to make critical decisions based on state-of-the-art technology. However, it should also be noted that the recommendations of international institutions regarding the selection of personal protective equipment for rescuers often refer to the concentrations corresponding to the individual Acute Exposure Guideline Levels (AEGL). Those values are not included in the national guidelines for the organization of rescue in the event of CBRN incidents. It is worth considering whether, in subsequent updates of the rules on the organization of chemical and ecological rescue, it would not be worthwhile to provide specific concentration limits corresponding to, for example, AEGL, for example for substances with which rescuers most often deal. Placing such information in one document, without the need to search in other source materials, would certainly facilitate the decision-making processes in the area of hazard zone designation, as well as the selection of PPE.

Author contributions

All authors made a draft of the manuscript, KB prepared the introduction, MG prepared the methodology, personal protection equipment during CBRN incidents, selection of PPE based on the risk scenarios, discussion and conclusion. KB has made critical fixes. All authors approved the final version of the manuscript for submission.

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Conflicts of Interest

The authors declare no conflicts of interest.

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