

COMPARATIVE ANALYSIS OF PHYSICOCHEMICAL CHARACTERISTICS OF CHEMICAL WARFARE AGENTS AND THEIR SIMULANTS

Gvozden Tasić, PhD

VINČA Institute of Nuclear Sciences, University of Belgrade, Serbia

Milica Ćurčić, MSc¹

VINČA Institute of Nuclear Sciences, University of Belgrade, Serbia

Ivana Perović, PhD

VINČA Institute of Nuclear Sciences, University of Belgrade, Serbia

INTRODUCTION

The modern security environment is characterized by several different classical security threats but also asymmetric and hybrid threats. One of the classic threats accessible to by both state and non-state actors is the use of a chemical weapon. Chemical weapons are among the most destructive weapons of mass destruction, as evidenced by their consequences, unpredictability, and diversity of action.

During the 20th century, humanity witnessed the devastating effects of chemical warfare agents (CWA) used as a means of mass destruction. Historically speaking, it has always been treated as a dishonourable means of warfare, but after the horrors that occurred due to its use in the middle of the twentieth century, it was finally banned. The reason prevailed and the Chemical Weapons Convention (CWC) (Articles | OPCW n.d.) entered into force in 1997, prohibiting the development, production, stockpiling, and use of chemical weapons. CWA have been used on several occasions in the last three decades (Picard et al. 2019), raising a necessity for scientific research and technological development of means for their detection, decontamination, and protection of human lives and the environment, as well as developing proper security procedures and protocols.

¹ milica.curcic@vin.bg.ac.rs

The CWC includes three schedules (list of chemicals), each associated with legally binding obligations for the signatory countries. Chemical compounds directly usable as CWA (or CWA precursors) and having no peaceful purpose are listed in Schedule 1, toxic chemicals which may be used as CWA (or precursors) with commercial application not prohibited under this Convention but not produced in large quantities are listed in Schedule 2, while those chemical compounds which may be used as CWA (or precursors) with significant commercial application not prohibited under this Convention produced in large quantities are listed in Schedule 3. Due to associated legal limitations and the fact that they are extremely hazardous and lethal, CWA can be used in a strictly controlled environment – licensed laboratories and isolated platforms with strict safety measures and protocols by trained personnel.

However, despite all prohibitions, non-state actors such as terrorist groups are determined to find ways to acquire and use it. The basic characteristics and the hidden period of action give a great advantage to chemical weapons over conventional weapons. On the other hand, in order to provide an adequate response, professional services need to have training that is as similar as possible to real conditions. In the case of a chemical weapons threat, this is not an easy task.

RELEVANT PHYSICOCHEMICAL PROPERTIES OF CWA

The CWA have different characteristics and belong to various classes of chemical compounds. The classification can be done by their volatility, chemical structure or physiological effects (Ganesan et al., 2010). If volatility is chosen as a classification criterion, one can distinguish between persistent (less volatile agents such as HD and VX) and non-persistent agents (more volatile agents such as phosgene, chlorine, GB, etc.). The more volatile an agent, the quicker it evaporates and disperses. Based on their chemical structure, they can be classified as organophosphorus, organosulfur and organofluorine compounds and arsenicals. If physiological effects that CWA produce on humans are taken into consideration, they can be classified as nerve agents, vesicants (blistering agents), blood agents, choking agents, riot-control agents, psychomimetic agents and toxins. VX and G-series agents are nerve agents and affect the functioning of the nervous system. They belong to a group of organophosphorus compounds and act as irreversible inhibitors of the enzyme acetylcholinesterase (AChE). This enzyme is responsible for hydrolyzing neurotransmitter acetylcholine (ACh) which can be found in the synaptic cleft (neuromuscular or nerve-gland junction). During transmission of nerve signals through synapsis, a small quantity of ACh is continuously liberated and hydrolyzed by AChE. Inhibition of AChE, by the creation of permanent phos-



phorus bond with nerve agent causes accumulation of ACh, leading to overexcitation or paralysis. HD and L are blistering agents or vesicants. Vesicants are toxic compounds that produce skin injuries resembling those caused by burns. These agents - on inhalation - affect the upper respiratory tract as well as the lungs, producing pulmonary edema. These agents can also cause severe eye injuries. There are two forms of vesicants: mustards and arsenicals.

Table 1. *Physicochemical properties of CWA*

| Physicochemical property | Sulphur Mustard HD | Lewisite L | Sarin GB | Soman GD | Tabun GA | VX |
|--|----------------------------------|--------------------------------|-----------------------|-----------------------------|--------------------------------|--------------------|
| ^a Colour | colourless to pale yellow liquid | colourless to brownish liquid | colourless | colourless to brown liquid | colourless to brown liquid | colourless |
| ^a Odour | garlic or horseradish | varies, may resemble geraniums | almost none when pure | fruity, camphor when impure | faintly fruity, none when pure | none |
| ^a Molecular weight (g/mol) | 159.08 | 207.35 | 140.1 | 182.18 | 162.3 | 267.38 |
| ^a Density (g/cm ³) | 1.27 | 1.89 | 1.09 | 1.022 | 1.073 | 1.0083 |
| ^a Vapour pressure at 20°C (Pa) | 11.5 | 69.3 | 331.52 | 46.9 | 4.92 | 0.016 |
| ^b Volatility at 25°C (mg/L) | 0.92 | 5 | 22 | 4 | 0.61 | 0.011 |
| ^c Melting point (°C) | 14.5 | -1.2 | -57 | -42 | -50 | <-51 |
| ^c Boiling point (°C) | 218 | 196 | 157 | 198 | 248 | 292 |
| ^b Dynamic viscosity at 20°C (mPas) | 4.49 | 2.19 | 1.55 | 3.69 | 2.6 | / |
| ^b Persistency relative to water at 15°C | 67 | / | 3.13 | 18.3 | 58.9 | / |
| ^b Vapour density relative to air | 5.5 | / | 4.86 | 6.33 | 5.6 | 9.25 |
| ^b Latent heat of evaporation (J/g) | 393.9 | 243 | 355.7 | 328.9 | / | 375 |
| ^b Surface tension (mN/m) | 42.88 | / | 26.65 | 26.51 | / | 31 |
| ^c log Kow | 2.41-2.55 | 2.56 | 0.3 | 1.78 | 0.394 | 2.09 |
| ^c Solubility (mg/l) at 25°C | 684 | 500 | 1x10 ⁶ | 2.1x10 ⁻⁴ | 7.2x10 ⁻⁴ (20°C) | 3x10 ⁻⁴ |
| ^a LD ₅₀ (mg/kg) | 100 | 30 | 24.28 | 0.71 | 21.42 | 0.071 |
| ^a LC ₅₀ (mg/m ³) | 900 | 1400 | 35 | 35 | 70 | 15 |

a-(OPCW, n.d.)

b-(Bokan et al., 2004)

c-(Bartelt-Hunt et al., 2008)



Application, dispersion methods, persistency, identification, detection, toxicity, medical treatment, protection, prevention, decontamination, storage, etc. can all be subject of scientific research or training activities. They are strongly dependent on different physicochemical properties of CWA. The most significant physical properties for the application of CWA are state of matter, colour, odour, vapour pressure, boiling and melting point, viscosity, relative vapour density, diffusion, latent heat of evaporation, aerosol formation and surface tension (Bokan et al., 2004). Chemical properties of interest include: molecular structure, hydrolysis, chemical reactivity with acids and bases, oxidizing and reducing agents, reactions with different materials, thermic stability, etc. (Bokan et al., 2004). Toxicity of CWAs is usually given as LD_{50} or LC_{50} . LD_{50} is the amount of a toxic agent, given at once, which causes the death of 50% (one half) of a group of test subjects. LC_{50} is the concentration of a toxic agent in mg/m^3 (air), which applied for 1 minute causes the death of 50% of a group of test subjects. Some of the CWA properties are presented in Table 1. Finding data common to all CWA proved to be a demanding task. The data have been collected from different sources (Bartelt-Hunt et al., 2008; Bennett, 1984; Bokan et al., 2004; USAMRICD, 2007).

CWA SIMULANTS

One way to avoid accidents and achieve adequate safety levels during scientific research, testing equipment and training of different personnel is to use CWA simulants. CWA simulants are less or not at all toxic chemicals that resemble the agent in molecular structure or physicochemical properties of interest. It must be pointed out that there is no such simulant that would possess all of the corresponding aspects and properties of an agent. If that were the case, it would be toxic as well. Since there is no ideal CWA simulant that can represent all targeted properties of CWA, a number of different chemicals have been used for particular tasks. This is not a definite number: as the research, testing and training activities in CBRN field grow, so does the list of possible simulant compounds.

The simplest and the most obvious criteria to classify them is the type of CWA for which they are used as simulants. In this manner one can distinct between HD, L, GA, GB, GD, VX, etc. simulants. In this paper the focus will be on HD, G-series, and VX simulants.

HD simulants: Chloroethyl ethyl sulphide (CEES) is widely used and recognized as its most relevant simulant: its half-mustard (HM) molecular structure makes it suitable for a wide scope of applications (Picard et al., 2019)[2], 2-chloroethyl methyl sulphide (CEMS), 2-chloroethyl phenyl sulphide (CEPS), methyl salicylate (MS), diethyl adipate, diethyl malonate (DEM), dimethyl adipate (DMA), diethyl



pimelate, have all been used in the investigation of the environmental fate of HD (Bartelt-Hunt et al., 2008).

G-series simulants: Organophosphonates diethyl cyanophosphonate (DCNP) and diisopropylfluorophosphate (DFP) have been regarded, for a long time, as analogues of choice; phosphonates isopropyl nitrophenyl methyl phosphonate (NIMP) and ethyl nitrophenyl methyl phosphonate (NEMP) have gained in popularity due to UV analysis possibility [Picard]; dimethyl methyl phosphonate (DMMP), diethyl ethyl phosphonate (DEEP), diisopropyl methylphosphonate (DIMP), triethylphosphate (TEP), trimethylphosphate (TEM), 1-butanethiol (BUSH), diethyl ester phosphonic acid (DEHP), diethyl malonate (DEM), diisopropylfluorophosphate (DFP), bis(2-ethyl hexyl) phthalate (DOP), dipropylene glycol monomethyl ether (DPGME), ethyl chloroacetate (ECA), diphenyl chlorophosphate (DPCP), pinacolyl methylphosphonate (PMP), diethyl phosphoramidate (DEPA) have all been used in the investigation of environmental fate and detection (Bartelt-Hunt et al., 2008; Kanu et al., 2005).

VX simulants: there is currently no commercially available molecule mimicking the -S-(CH₂)₂-N(i-Pr)₂ key-motif involved in VX's bio-activity (this side chain simulating acetylcholine). In this sense, the phosphonothioate LG 61, phosphorothioates Demeton-S18 (and its methoxy analogue Demeton-S-methyl), Tetriso and PhX have been used as simulants, PhX being the closest alternative to VX [2]. For determining the environmental behaviour, detection and training purposes, amiton (VG), O,S-diethyl phenylphosphonothioate (DEPPT), malathion, parathion, diethylphthalate (DEP), diethyl sebacat (DES), 2-(butylamino) ethanethiol (2-BAET), etc. have also been used (Bartelt-Hunt et al., 2008; Kanu et al., 2005).

Some of the stated simulants, such as DMMP, DIMP, VG, etc. are sufficiently toxic to be used as chemical weapons themselves, and some are used as precursors to CWA. Those compounds have been listed as Schedule 2 substances in the Chemical Weapon Convention and should be treated cautiously.

The molecular structure of some typical simulants and corresponding CWA are given in Fig.1 Different physicochemical properties of all possible simulants can be found in the literature (Bartelt-Hunt et al., 2008; Bennett, 1984; Bokan et al., 2004; Kanu et al., 2005; Lavoie et al., 2011; Matatagui et al., 2011; McKenna et al., 2017; Moshiri et al., 2012; Picard et al., 2019; USAMRICD, 2007). Obtaining all these data is a more difficult task than for the CWA. Some significant physicochemical properties of typical simulants are given in Table 2.



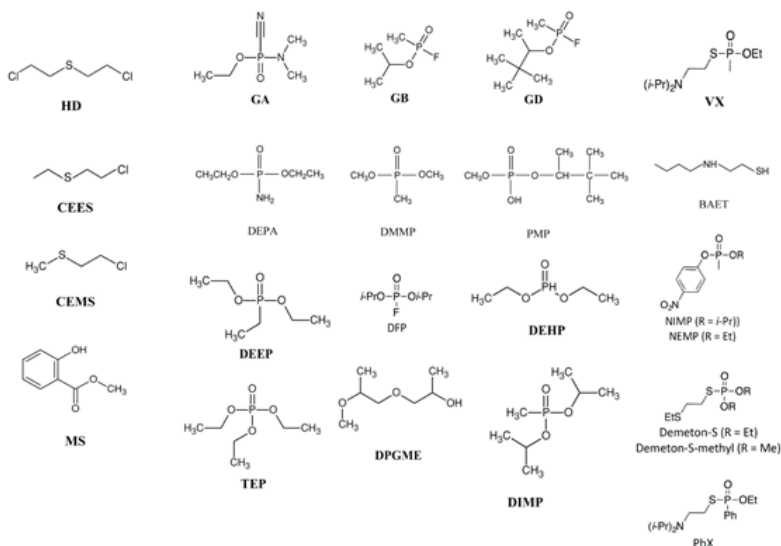


Figure 1. Molecular structure of common CWA and their simulants

Table 2. Physicochemical properties of common CWA simulants

| Simulant | CWA | CAS number | Molecular weight (g/mol) | melting point (°C) | boiling point (°C) | vapour pressure (Pa) | Log K_{ow} | LD ₅₀ (mg/kg) |
|-----------------------|-------|------------|--------------------------|--------------------|--------------------|----------------------|--------------|--------------------------|
| ^a CEES | HD | 693-07-2 | 124.63 | -48.6 | 156.5 | 453.3 | 2.2 | 252 (rat oral) |
| ^a CEMS | HD | 542-81-4 | 110.6 | -61 | 132 | 1197.2 | 1.62 | ND |
| ^a MS | HD | 119-36-8 | 152.15 | -8 | 223 | 5.33 | 2.55 | 887 (rat oral) |
| ^a DEEP | GA,GB | 78-38-6 | 166.16 | -13 | 198 | 42 | 0.66 | 2330 (rat oral) |
| ^a TEP | GA,GB | 78-40-0 | 182.16 | -56 | 215 | 52 | 0.8 | 1180 (mouse oral) |
| ^a DEHP | GD | 762-04-9 | 138.1 | <25 | 138 | 1493.2 | 3.01 | 3900 (rat oral) |
| ^a DFP | GB,GD | 55-91-4 | 184.15 | -82 | 183 | 77.3 | 4.3 | 5 (rat oral) |
| ^a DMMP | GB,GD | 1445-75-6 | 180.19 | <25 | 121 | 37 | 1.03 | 8210 (rat oral) |
| ^a Amiton | VX | 78-53-5 | 269.34 | <25 | 110 | 0.036 | 3.94 | 3.3 (rat oral) |
| ^a Malation | VX | 121-75-5 | 330.36 | 2.8 | 156 | 4.5x10 ⁻⁴ | 2.36 | 290 (rat oral) |
| ^b BAET | VX | 5842-00-2 | 133.26 | <25 | 242.7 | 0.0±53.3 | 1.697 | / |
| ^c NIMP | VX | 3735-97-5 | 259.196 | <25 | 362.5±34 | 0.0±106.6 | 1.5 | 0.45 (rat oral) |

(Bartelt-Hunt et al., 2008)

(2-(Butylamino)Ethanethiol 97 5842-00-2, n.d.)

(Grigoriu, 2019)



SELECTION OF A SIMULANT

In practice, however, there is no need for the absolute resemblance between an agent and a simulant. Depending on a phenomenon of interest, simulant will be chosen among a number of different chemical compounds according to specific molecular or physicochemical features, e.g. similarity in kinetic viscosity, density and colour if used for visual inspection of its interaction with various substrates, or similarity in molecular formula (presence of specific atomic groups) and volatility if used for studying detection techniques. These data for both CWA and potential simulants can be found in the literature. Investigations that utilise simulants give a strong indication of CWA behaviour regarding the phenomenon of interest and usually are not identical to CWA. However, in most cases, it is more than enough for adequate extrapolation on targeted CWA behaviour. Figure 2 schematically represents the process of choosing the simulant for a specific task.

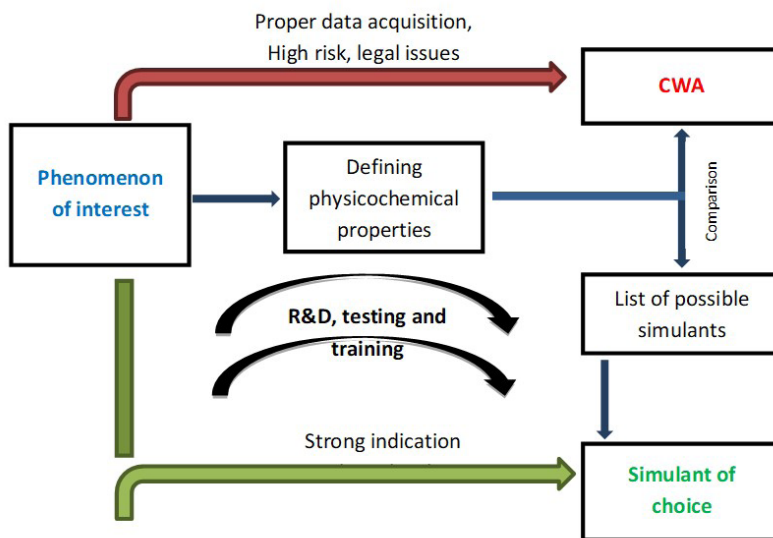


Figure 2. Selection of a CWA simulant - schematic representation

Usually, appropriate simulants have been chosen by experts, depending on a task in front of them, mainly by their intuition and similarity in physical properties, as already explained. However, there have been a number of attempts to automate the simulant identification process by computational methods based on chemical similarity software and algorithms used to search through databases of agents and simulants' molecular structures and physicochemical properties (Lavoie et al., 2011). This approach has been routinely applied in the pharmaceutical industry and medical research in

drug discovery. Furthermore, once experimental data on simulants and reference materials have been gathered, the same computational approach can be used to address the behaviour of the targeted CWA.

Bartelt-Hunt et al. gave a thorough review of CWA simulants' application in investigations of CWA environmental behaviour (Bartelt-Hunt et al., 2008). Potential fate pathways for CWAs in the environment include different physicochemical and biological processes, such as volatilization, sorption, hydrolysis, photolysis, and microbial degradation. These processes have been widely utilised as remediation techniques and decontamination procedures for different toxic industrial chemicals (TIC) and have been a focus of scientific research for decades (Aćimović et al., 2017; Nikolić et al., 2017). As significant environmental pollutants TICs, such as polycyclic aromatic hydrocarbons (PAH) and a number of volatile organic compounds (VOC), pesticides, pharmaceuticals, etc. have similar molecular structures and similar environmental fates as CWA. This makes the research data on TICs a good starting point in both choosing a proper simulant or prediction of CWA behaviour. Depending on the investigated phenomenon, different simulants have been applied in a vast number of scientific investigations. For the sake of simplicity, sorption/desorption and hydrolysis will be presented in this paper as a phenomenon of interest for the process of choosing a proper simulant.

Prompt, sensitive and selective detection is crucial for minimizing the impact of undesirable CWA applications on both human lives and the environment. There are different types of commercially available hand-held detectors used by first responders. They are based on ion-mobility spectrometry (IMS), flame photometry (FP) and colorimetric methods. The first step in detector testing and detection techniques training is the application of CWA simulants. Again, for the sake of simplicity, we will focus on a selection of simulants for the investigation of IMS detection as an example of the process of choosing a proper simulant. Handheld IMS units are used by first responders to help determine the nature and magnitude of the chemical threat to the responders, the public, and the environment. IMS is a method for detecting and identifying volatile and semi-volatile organic compounds. This technique is based on the determination of mobilities in electric fields of gas phase ions derived from constituents in a sample. IMS analyser may be used over a large range of conditions (ambient pressure, air as drift gas) while exhibiting fast response and reliable performance (high sensitivity, recording of ion mobility spectra).



Sorption/Desorption

If the phenomenon of interest is sorption and desorption of CWA on a sorbent (e.g. active carbon), the choice of simulant should take into consideration properties such as the n-octanol/water partition ratio or coefficient - $\log K_{OW}$ and molecular size (Table 2). Sorption/desorption processes are governed by the $\log K_{OW}$ values, while their rates are governed by the diffusion of sorbates through the intraparticle polymeric matrix and/or porous structure of the sorbent (Bartelt-Hunt et al., 2008). According to Bartelt-Hunt if these criteria were taken in consideration, the best choice for HD simulants would be CEES and CEMS. For GA and GB simulants the best choice would be DEEP and TEP and for GD, DEHP. For VX the best match is malathion.

Hydrolysis

Hydrolysis, as a phenomenon of interest, depends primarily on the presence of the bonds at which the hydrolysis reaction occurs in the CWA agent, which means that the main criteria for simulant choice should be similar molecular structure (Bartelt-Hunt et al., 2008; McKenna et al., 2017; Moshiri et al., 2012). The chosen simulants should also form the same or similar hydrolysis products. GB and GD hydrolysis occurs at the P-F and P-alkoxy bonds resulting in the formation of methylphosphonic acid. In this case, Bartelt-Hunt et al. state that the best choice for a simulant is DFP, due to the presence of P-F bond and overall structural similarity. By the same criteria, CEES is the best simulant choice for hydrolysis of HD, due to the presence of the ethyl chloride functional group, and DEPPT is the best as the simulant for VX due to the presence of P-S and P-O bonds and similar distribution of products originating from the bond breakage.

IMS detection

Portable, handheld IMS (Ion mobility spectrometry) detectors are widely used for field detection of CWA. Since these instruments are limited to gas phase samples, the choice of simulants should take into consideration the properties such as volatility, vapor pressure and vapor density, as well as the similarity in molecular structure. For instance, Kanu et al. (Kanu et al., 2005) have investigated IMS detection of CWA and their degradation products on the surfaces utilizing dimethyl methyl phosphonate, DMMP; pinacolyl methylphosphonate, PMP; diethyl phosphoramidate, DEPA; 2-chloroethyl ethyl sulfide, CEES; and 2-(butylamino) ethanethiol,



BAET). DMMP was chosen as a simulant for the presence of a P=O, P-CH₃ and P-OCH₃ functional groups that are found in both GB and GD. PMP was chosen as a simulant because its structure is identical to that of GD, except that the fluorine atom in GD is substituted by an OH group. DEPA was chosen as a simulant because it contains a P=O, P-NH₂ and P-OCH₂CH₃ functional groups which are found in GA. Similarly, 2-BAET was selected as a simulant because it possesses both C-S and C-N bonds found in the functional groups of VX which are attached to the phosphorus atom. One of these simulants, CEES, was used as a structurally identical simulant for HD with the exception of a missing chloride atom.

CWA MIMETICS

As it was already stated, the main reason for the utilisation of simulants is that they are less or not at all toxic, implicating no legal issues for their application. However, in some cases toxicity itself is the phenomenon of interest or is closely related to it. For instance, in the process of training the first responders, the use of CWA and toxic industrial chemicals makes the exercise scenario more realistic and more stressful. This builds trainees' confidence more effectively than training with simulants (Tasić, Ćurčić, Lazović, 2021). Any substance that can be legally used and still exhibit a sufficient level of toxicity for the specific task can be referred to as CWA mimetic and thus be distinguished from the other simulant compounds.

Comparison of toxicity levels of CWA and some typical simulants/mimetics in terms of LD₅₀ or LC₅₀ values can be done by data given in Table 1 and Table 2.

MIXTURE SIMULANTS

All CWA simulants presented in previous chapters are single compound simulants. One specific compound has been chosen as a simulant depending on a task in front of researchers, educators and engineers. Molecular and physicochemical features of a simulant differ more or less from those of the targeted CWA which makes the extrapolation of CWA behaviour correspondingly uncertain. The more similar the properties of interest in the simulant and CWA are, the more precise prediction of the CWA behaviour can be made.

One way to overcome this obstacle is to use specifically designed simulants as a mixture of different compounds in order to obtain the desirable level of similarity in certain physicochemical properties with simulated CWA. This approach has



been used by some CBRN companies and militaries. The composition of simulants is usually considered a trade secret or classified data. For instance, the company OUVRY from Lyon, France produces the SIM-KIT® with HD, GB and VX simulants with the same physicochemical characteristics as the real agents in terms of persistence, colour, viscosity, volatility and behaviour in water, which makes them suitable for realistic CBRN trainings, colorimetric detection (detection on papers such as CALID3) and flame or ion mobility spectrometry (detection and identification by devices such as AP2C, AP4C, LCD3). The main component for HD simulant is methyl salicylate, for GB is dipropylene glycol monomethyl ether and for VX is polypropylene glycol monobutyl ether. Each simulant contains a proper solvent, colouring agent and additional compounds to adjust the above stated properties.

The mixture simulants are more similar in targeted properties to CWA than any single-compound simulant; they are easy to use, safe for users and the environment, and biodegradable. The disadvantage is the limited scope of application since they have been designed for specific tasks. Sometimes they cannot be detected properly by standard detection techniques, or the detection time is prolonged.

CONCLUSION

In order to provide an adequate and complete response to the threat of the use of chemical weapons, first responders must undergo training that is as similar as possible to the real-life situation. Legal and safety issues related to CWA research, training and testing activities can be avoided by the use of CWA simulants. A comparison of literature data shows that there is no unique simulant for specific CWA, but rather a number of different compounds which can be used as simulants depending on the phenomenon of interest and related physicochemical properties. Comparison of CWAs and simulants' physicochemical properties relevant to the phenomenon of interest is a desirable method for simulant selection. CWA behaviour regarding the phenomenon of interest can be extrapolated from the behaviour of corresponding simulants. The more similar properties of a CWA and a simulant are, the better prediction of the CWA behaviour can be made. Chemical compounds which could be used as CWA simulants can be classified by the type of CWA they mimic. If the property of interest is toxicity, then any substance that can be legally used and still exhibit a sufficient level of toxicity for the specific task can be referred to as CWA mimetic. The desirable level of similarity in certain physicochemical properties with simulated CWA can be achieved by simulants designed as a mixture of different compounds. However, they have a limited scope of application since they have been designed for specific tasks.



ACKNOWLEDGEMENTS

This paper was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia; Grant No. 451-03-68/2022-14/200017.

REFERENCES

- 2-(Butylamino)ethanethiol 97 5842-00-2. (n.d.). <https://www.sigmaaldrich.com/RS/en/product/aldrich/b89507>
- Aćimović, D. D., Karić, S. D., Nikolić, Ž. M., Brdarić, T. P., Tasić, G. S., Marčeta Kaninski, M. P., & Nikolić, V. M. (2017). Electrochemical oxidation of the polycyclic aromatic hydrocarbons in polluted concrete of the residential buildings. *Environmental Pollution (Barking, Essex : 1987)*, 220(Pt A), 393–399. <https://doi.org/10.1016/j.envpol.2016.09.075>
- Bartelt-Hunt, S. L., Knappe, D. R. U., & Barlaz, M. A. (2008). A Review of Chemical Warfare Agent Simulants for the Study of Environmental Behavior. *Critical Reviews in Environmental Science and Technology*, 38(2), 112–136. <https://doi.org/10.1080/10643380701643650>
- Bennett, S. R. (1984). *Environmental Hazards of Chemical Agent Simulants*.
- Bokan, S., Čižmek, A., Ilijaš, B., Jukić, I., Orehovec, Z., & Radalj, Ž. (2004). *Oružja za masovno uništenje: nuklearno-kemijsko-biološko i toksinsko oružje*.
- Ganesan, K., Raza, S. K., & Vijayaraghavan, R. (2010). Chemical warfare agents. *Journal of Pharmacy & Bioallied Sciences*, 2(3), 166–178. <https://doi.org/10.4103/0975-7406.68498>
- Grigoriu, N. (2019). Study Regarding the Inhibition of Acetylcholinesterase by Isopropyl 4-Nitrophenyl Methylphosphonate. *Biomedical Journal of Scientific & Technical Research TA - TT -*, 14(2). <https://doi.org/10.26717/BJSTR.2019.14.002539> LK - <https://washingtonstate.on.worldcat.org/oclc/8049572475>
- Kanu, A. B., Haigh, P. E., & Hill, H. H. (2005). Surface detection of chemical warfare agent simulants and degradation products. *Analytica Chimica Acta*, 553(1), 148–159. <https://doi.org/https://doi.org/10.1016/j.aca.2005.08.012>
- Lavoie, J., Srinivasan, S., & Nagarajan, R. (2011). Using cheminformatics to find simulants for chemical warfare agents. *Journal of Hazardous Materials*, 194, 85–91. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2011.07.077>
- Matatagui, D., Fernández, M. J., Fontecha, J., Santos, J. P., Gràcia, I., Cané, C., & Horrillo, M. C. (2011). Discrimination and classification of chemical warfare agent simulants using a Love-wave sensor array. *Procedia Engineering*, 25, 23–26. <https://doi.org/https://doi.org/10.1016/j.proeng.2011.12.006>



- McKenna, J., Dhummakupt, E. S., Connell, T., Demond, P. S., Miller, D. B., Michael Nilles, J., Manicke, N. E., & Glaros, T. (2017). Detection of chemical warfare agent simulants and hydrolysis products in biological samples by paper spray mass spectrometry. *Analyst*, *142*(9), 1442–1451. <https://doi.org/10.1039/C7AN00144D>
- Moshiri, M., Darchini-Maragheh, E., & Balali-Mood, M. (2012). Advances in toxicology and medical treatment of chemical warfare nerve agents. *Daru : Journal of Faculty of Pharmacy, Tehran University of Medical Sciences*, *20*(1), 81. <https://doi.org/10.1186/2008-2231-20-81>
- Nikolić, V. M., Karić, S. D., Nikolić, Ž. M., Tošić, M. S., Tasić, G. S., Milovanovic, D. M., & Kaninski, M. P. M. (2017). Novel photochemical advanced oxidation process for the removal of polycyclic aromatic hydrocarbons from polluted concrete. *Chemical Engineering Journal*, *312*, 99–105. <https://doi.org/https://doi.org/10.1016/j.cej.2016.11.117>
- OPCW. (n.d.). *Physicochemical Properties & Relative Toxicity of Chemical Warfare Agents*.
- Picard, B., Chataigner, I., Maddaluno, J., & Legros, J. (2019). Introduction to chemical warfare agents, relevant simulants and modern neutralisation methods. *Org. Biomol. Chem.*, *17*(27), 6528–6537. <https://doi.org/10.1039/C9OB00802K>
- Tasić, G., Ćurčić, M., Lazović, I. (2021). The role of CBRN live agent training in education of first responders. *XI International Scientific Conference Archibald Reiss Days*, Conference proceedings (page 379).
- USAMRICD. (2007). *Medical Management of Chemical Casualties Handbook* (4th ed.). US Army Medical Research Institute of Chemical Defense.

