

REVIEW PAPER

Recent Advances in Decontamination of Chemical Warfare Agents

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ABSTRACT

The recent turmoil and volatile situation in many countries and the increased risk of terrorist activities have raised alarm bells for the field of defense against toxic chemical/materials. These situations poses threats to society as terrorists can take advantage of such situations to strike and cause public mayhem. A number of chemicals have the potential of being used as chemical warfare (CW) agents. CW agents could immediately kill or incapacitate the affected individuals even when they are present in very low concentration. CW agents should be removed quickly to minimize their deleterious health effect. There is no single decontamination system that can be used against all types of chemical warfare (CW) agents. The review briefs about different decontamination processes and approaches for chemical decontamination and also discusses about various decontamination products available globally.

Keywords: Chemical warfare agents, contamination, decontamination, nerve agents, decontamination process

1. INTRODUCTION

Disasters involving chemical warfare agents or toxic industrial chemicals are of great concern because of the proclivity for such incidents/accidents to cause morbidity and mortality in large numbers. The release of such toxic agents during overt war is a possibility despite various conventions in place. It could be the result of compromise in safety and security resulting in accidental release, or a consequence of a natural calamity, or an intentional act by terrorists to create havoc and mayhem. Attack on civilian populations by the release of sarin nerve gas in Tokyo subway system (1995) is a common example of deliberate release of chemicals by terrorists¹. During the Iran-Iraq war in 1980, Kurdish civilian population of Halabja was targeted with nerve agents²⁻³. Release of poisonous gas methyl isocyanate (MIC) in December 1984 from the Union Carbide Plant in Bhopal is an example of accidental release⁴⁻⁵. Natural calamities leading to chemical disasters are exemplified by damage to phosphoric acid sludge containment during the Orissa super cyclone in 1999 and the release of acrylonitrile at Kandla Port, during an earthquake (2001). During Sichuan earthquake August 30, 2008 - in the city of Shifang, two chemical plants collapsed and led to leakage of some 80 tons of liquid ammonia.

A chemical weapon's attack can be carried out in a defined localized area that is densely populated so as to result in mass casualties. Mode of dispersion of CW agent could be vaporization, spraying or other methods in an effort to affect the largest possible number of military population and civilians. The level of destruction caused by intentional release of these agents depends upon a number of factors. These include type of agent, their toxicity, concentration of agent, its

volatility, route of exposure, duration of exposure, location and meteorological conditions. In an open area of environment, the contaminant would become more diluted and the effect would be less intense. While in a closed environment small amount would be able to cause more deteriorative effect⁶⁻¹⁰.

1.1 Chemical Agents

Chemical agents are chemical substances that are intended for use in warfare or terrorist activities to kill or seriously injure, and seriously incapacitate people through their physiological effects¹¹. Chemical agents attack the organs of the human body in such a manner that it prevents those organs from functioning normally. The most common chemical agents are the nerve agents, Tabun (GA), Sarin (GB), Soman (GD), GF, and VX; the blister agents, sulfur mustard (HD) and nitrogen mustard (HN); and the arsenical vesicants, Lewisite (L).

1.2 Toxic Industrial Chemicals/Materials

These are chemicals other than chemical warfare agents that have harmful effects on humans. While exposure to some of these chemicals may not be immediately dangerous to life and health, these compounds may have extremely serious effects on an individual's health after multiple low-level exposures. Toxic industrial materials (TIM) is a specific type of industrial chemical, i.e., one that has a LC₅₀ value (lethal concentration of a chemical vapor or aerosol for 50 per cent of the population multiplied by exposure time) less than 100000 mg/min/m³ in any mammalian species and is produced in quantities exceeding 30 tons per year at one production facility. The easy approach to prepare or acquire them and their ability to make a significant impact on the masses make them open to be used by

the terrorists to create havoc and pandemonium¹¹⁻¹³.

Mechanism of action nerve agents inhibit cholinesterase enzyme in plasma, erythrocytes and at cholinergic nerve endings in tissues. Once tissue cholinesterase is inhibited by the nerve agent, the enzyme cannot hydrolyze the neurotransmitter acetylcholine. Consequently, acetylcholine accumulates and causes prolonged action on the affected tissues. Enzyme activity will slowly return to normal without antidotes, but only as new cholinesterase is synthesized or with erythrocyte turnover.

The exact mechanism of action of blistering agents is not known. They have the ability to alkylate a very wide range of biologically important molecules. In deoxyribonucleic acid (DNA), monofunctional adducts are predominantly formed (the

secondary chloroethyl function is converted into hydroxyethyl), but bifunctional binding, leading to formation of cross-links, does occur. Alkylation of ribonucleic acid (RNA), proteins, cellular membrane components and crosslinks between DNA and proteins can be the cause of cellular damage¹².

Tables 1-5 summarizes the properties of different chemical warfare agents, their physical characteristics, means of exposure and treatment strategies to be followed¹⁴⁻¹⁶.

2. CONTAMINATION

Any form of unwanted hazardous material that physically remains deposited on the personnel, equipment, structures and areas (limiting the utilization of these resources) is termed as contamination. Contamination renders the equipment and

Table 1. Physicochemical properties and lethal doses of different nerve agents

Name	Physical characteristics	Molecular weight	Density (g/cm ³)	Boiling point (°F)	Freezing point (°F)	Solubility in water (%)	LD ₅₀ (skin, mg/kg)	Means of exposure	Treatment
Tabun (GA)	Colorless to brown liquid with odor ranging from none to fruity	162.3	1.073	464	18	10	1.1.5		
Sarin (GB)	Colorless liquid with fruity odor	140.1	1.089	316	-69	Miscible with water	24	Skin contact and/or inhalation.	Atropine, Pralidoxime chloride and Diazepam in combination.
Soman (GD)	Colorless liquid with fruity odor	182.2	1.022	388	-44	2	10-15		
VX	Amber colored liquid with amine odor	267.4	1.008	568	<-60	Slightly	<5		

Table 2. Physicochemical properties of different blistering agents

Name	Physical characteristics	Molecular weight	Density (g/cm ³)	Boiling point (°F)	Freezing point (°F)	Solubility in water (%)	LD ₅₀ (skin, mg/kg)	Means of exposure	Treatment
Sulphur Mustard (HD)	Colorless, odorless liquid.	159.1	1.27 at 68°F	421	58	<1 %	100		No specific antidote. Treatment similar to burn injuries. Atropine solution for relieving blepharospasm. Systemic analgesics and antihistamines for the relief of itching and pain. Pharyngitis can be relieved by alkaline gargle.
Nitrogen mustard (HN3)	Colorless liquid, less volatile.	204.5	1.24 at 77°F	493	-26.7	Sparingly	10 (estimated)	Skin contact and/or inhalation	Specific antidote is British anti Lewisite (2,3-dithio captopropanol) for both topical and systemic administration. Other treatment options are similar to that of mustards.
Lewisite (L1)	Colorless, with metallic odor.	207.4	1.89 at 68°F	374	64.4 to 32.18	Insoluble	30		

Table 3. Physicochemical properties of different cyanogenic agents (blood agents or systemic agents)

Name	Physical Characteristics	Molecular weight	Density (g/cm ³)	Boiling point (°F)	Freezing point (°F)	Solubility in water (%)	LD ₅₀ (skin, mg/kg)	Means of exposure	Treatment
Hydrogen cyanide (AC)	Heavier and highly volatile gas	27.03	0.990 at 68°F	78.26	8	Highly soluble	100 (Liquid)	Inhalation	Treatment must be rapid to be effective. Artificial respiration and oxygen can be given as first aids. Administration of anti-dots like amyl nitrite, sodium nitrite and 4-dimethylaminophenol, Hydroxocobalamine and kelocyanor. Supportive therapy includes administration of diazepam, sodium bicarbonate, and methylene blue.
Hydrogen chloride (CK)	Highly volatile gas	61.48	1.18 at 68°F	55.04	19.58	Slightly	No data available		

Table 4. Physicochemical properties of different choking agents

Name	Physical characteristics	Molecular weight	Density (g/cm ³)	Boiling point (°F)	Freezing point (°F)	Solubility in water (%)	LCt ₅₀ (respiratory, mg-min/m ³)	Means of exposure	Treatment
Chlorine	Pungent green yellow gas	70.9	1.393 at 68°F	-29	-149	1.5	No data available	Inhalation	Victim should be allowed to take fresh air, artificial respiration along with the administration of cortisone and sodium bicarbonate. Codeine for suppression of cough. Air way obstruction can be relieved by theophylline and prostaglandinE1.
Phosgene	Gas with little distinguishing odor	98.92	1.381 at 68°F	46	-198	--	3200	Inhalation	
Diphosgene	Colorless liquid	197.85	1.65 at 68°F	262	-71	--	3000-3200	Inhalation	

Table 5. Physicochemical properties of different riot control agents (lachrymators)

Name	Physical characteristics	Molecular weight	Density (g/cm ³)	Boiling point (°F)	Melting point, (°F)	Solubility in water (%)	LCt ₅₀ (respiratory, mg-min/m ³)	Means of exposure	Treatment
Chloroacetophenone (CN)	Solid	154.59	1.324	478	129	Insoluble	7000-14000	Inhalation	
Chlorobenzylidenemalononitrile (CS)	Solid	188.61	1.389	590	201	Insoluble	61000	Inhalation	Immediate decontamination of eyes and skin with water. Calamine lotion for treating inflammation of skin.
Chlorobenzylidenemalononitrile (CR)	Solid	195	1.334	635	162	Insoluble	Not available	Inhalation	

areas useless and increases the chances of health hazards. Three fundamentals of contamination control measures include avoidance (pre-event situation), immediate or operational decontamination (during event measure) and clearance decontamination or contaminated items containment (as the post event measures). Contamination control includes avoiding, reducing, removing, or rendering harmless the hazards from source of contamination. Contamination avoidance prevents disruption to operations and organizations by minimizing unnecessary time in cumbersome protective postures and by minimizing decontamination requirements¹⁷.

3. DECONTAMINATION

Decontamination is defined as the reduction or removal of chemical agents so that they are no longer hazardous¹⁸. It is the procedure employed to remove hazardous materials from people and equipment, to prevent the spread of contaminants beyond a specific area and reduce the level of contamination to levels that are no longer harmful. Decontamination may be accomplished by removal of these agents by physical means or by chemical neutralization or detoxification (Fig. 1). For successful decontamination Decon Station Personnel and Medical First Responders should be trained, equipped, and clothed in a manner to safely decontaminate any exposed victim suspected of being contaminated. The work by Singh¹⁹, *et al.* and Seto²⁰ give a comprehensive idea of the requirements for successful decontamination.

Decontamination could be personal, casualty or personnel decontamination. Personal decontamination is decontamination of self i.e. the victim itself acts as responder and decontaminates with the available decontaminating agents. Technical decontamination is the process used to clean vehicles, personal protective equipment, etc. Personnel decontamination usually refers to decontamination of non-casualties. Clinical Decontamination is the medical procedure to treat patients affected by or contaminated with hazardous materials. Casualty decontamination refers to the decontamination of casualties by team of responders. Effective decontamination is necessary to contain and prevent further spread of contaminating agent²¹⁻²⁸. The objective of decontamination is to provide reassurance to

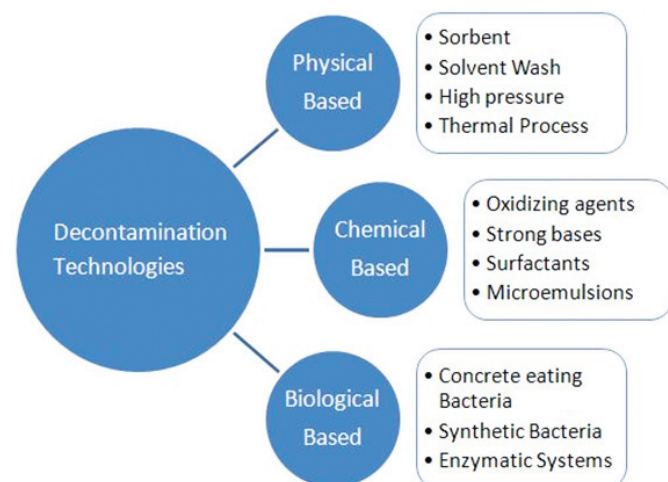


Figure 1. Decontamination technologies.

the victims/casualties that the decontamination process will reduce the potential effects of the contamination at or near the incident so as to prevent them from spreading contamination over greater areas including the protection of health facilities and hospital facilities²⁹.

Important points related to contamination with chemical agents should be kept in mind in the pre-event planning stage³⁰⁻³¹ are:

- What is the objective of decontamination?
- Whether it is to prevent further release or hazard reduction?
- Which is the best suitable decontamination method applicable?
- Cost involved in decontamination. The method employed should be cost effective. Minimum operational cost is desirable.
- Do we have any training or past experience in decontamination of such substances?
- Lessons learned from the past experiences ease the planning and operations. How to eliminate or reduce hazards of the substance?
- Status of generated waste is also an important factor that has to be kept in mind.

For non toxic and eco-friendly final waste generated in decontamination the steps involved are different from those employed for dangerous waste management.

3.1 Decontamination Process

A decontamination process refers to a method employed to destroy, reduce, or remove a contaminant to an acceptable level. Decontamination by removing clothes and flushing or showering with water is the most expedient and the most practical method for mass casualty decontamination. There are several methods used to decontaminate chemical agents and TIMs. These methods consist of physical, chemical, enzyme based decontamination and thermal processes³²⁻³³.

3.1.1 Physical Processes

Physical decontamination involves physically removing contaminant from the contaminated person or object by rubbing or scrubbing or abrasion process. For detoxification of agents other means of decontamination are required as this process only remove the agent and does not neutralize or detoxify it. Flushing or flooding contaminated skin or material with water or aqueous solutions can remove or dilute significant amounts of chemical agent. Scraping with a wooden stick (i.e., a tongue depressor or Popsicle stick) can remove bulk agent by physical means.

3.1.2 Chemical Processes

The process of removing or reducing the threat from a specific contaminant by rendering it less harmful through a chemical change (oxidation, reduction, complexation or chelation, etc.). Chemical processes involve the use of reactive or catalytic chemicals (sorbents) to neutralize the contaminants. Another means of decontamination would be necessary for chemical agent removal.

3.1.3 Enzyme Based Decontamination

The application of enzymes for protection against OP poisoning is a concept with exciting potential in the treatment of people exposed to both pesticide and chemical warfare agent (CWA). The toxic effects of organophosphorus (OP) compounds are largely attribute to the inhibition of the enzyme acetylcholinesterase. The OP compounds inhibit AChE by phosphorylation (organophosphonates by phosphonylation) of a serine hydroxyl located in the active site. Enzymes capable of detoxifying OPs include organophosphorus acid anhydrolase (OPAA) and organophosphorus hydrolase (OPH). There are studies on organophosphorus-hydrolyzing recombinant enzymes, organophosphorus acid anhydrolase and organophosphorus hydrolase³⁴⁻³⁵. Even for individual decontamination enzymes are useful³⁶.

3.1.4 Thermal Processes

Thermal processes remove the contaminants through vaporization. It should be noted that another means of decontamination is necessary for agent detoxification. Examples of decontamination equipment utilizing a thermal process are the Karcher mobile field laundry CFL 60 which both physically and thermally removes contaminants, and the Karcher AEDA1 decontamination equipment that employs a combination of low-temperature thermal technology and mechanical technology.

3.1.5 Dry Decontamination

The most effective dry decontamination method is the removal of the outer clothing accompanied by the provision of respiratory protection. Other methods for the removal of liquid or powder contaminant from victims are absorption, scraping or blotting e.g. the use of soil, cards etc. and tissue paper.

3.1.6 Wet Decontamination

The provision of dedicated or improvised methods of wet decontamination. Using the specialist equipment or adapted shower systems utilising hose reels, fog nozzles or the rinse/wipe/rinse method utilising buckets and high-density sponges.

3.2 Selection of Decontamination Technique

Due to wide variety of contaminants that varies in their nature and mechanism of contamination there is no single technology that can be applied in all circumstances of chemical contamination. When selecting a specific technique for decontamination, the following requirements must be considered³⁷⁻⁴³.

3.2.1 Safety

The application of the method should not result in formation of dusts and/or aerosols that increases chances of further spread of hazards due to inhalation. The applied technology should be safe both for victims as well as the responders. Further it should not form such reacting intermediate or end products that have deleterious effect on the environment or personnel.

3.2.2 Efficiency

The method should be capable of removing chemicals

from a surface to the level which would enable hands-on work instead of robotics; the method should be efficient with, a lower waste treatment and disposal category, thereby increasing the efficacy of system.

3.2.3 Cost-effectiveness

Where possible, equipment should be decontaminated and repaired for reuse; hence a cost effective one.

3.2.4 Waste Minimization

The method should not give rise to large quantities of secondary waste, the treatment and disposal of which would result in excessive requirements for work power and costs, thereby causing additional exposures.

3.2.5 Perspective of Industrialization

Due to the large quantities of contaminated materials involved, methods or techniques should not be labor-intensive, difficult to handle, or difficult to automate.

3.2.6 Broad Range

The decontamination systems must address a broad range of toxic military and industrial chemicals. The system should be robust enough to be applicable in wide range of chemicals under different climatic conditions and easy to handle.

3.3 Decontamination Products

The sensitivity of human skin to different chemicals and effect of different agents varies considerably. Man decontamination requires an entirely different approach from material decontamination. Following are the products available for man decontamination

3.3.1 RSDL

RSDL is a topical decontamination solution that reduces toxic effects from exposure to chemical warfare agents (VX and HD) and T-2 toxin. RSDL contains Dekon 139 and a small amount of 2,3 butadiene monoxime (DAM). These compounds are dissolved in a solvent composed of polyethylene glycol monomethyl ether (MPEG) and water. This solvent system is particularly important as it promotes the decontamination reaction by actively desorbing, retaining and sequestering the chemical agent, while the active ingredient (Dekon 139) chemically reacts with, and rapidly neutralizes the vesicant chemical or the organophosphorous nerve agent. Applying RSDL to skin with a cotton swab effectively decontaminates nerve agents such as VX, and some thickened agents, including thickened VX and thickened mustard, a blister agent. This reaction starts immediately and neutralization is usually complete within two min.

The disadvantage associated with RSDL is that it leaves an oily residue on skin and can make soldiers uncomfortable while carrying out certain military activities.

3.3.1 Sandia Foam

Sandia foam, also referred to as DF-100 foam, is a formulation of Sandia National Laboratories, Albuquerque, New Mexico, United States. When mixed at the point of

application, the formulation generates foam that changes to a liquid in 30 min. DF-100 has been reported to perform well against nerve agents like GD (35 fold protective ratio) and VX (72 fold protective ratio). The protective ratio is the ratio of LD50 for cutaneous exposure in animals after and before decontamination.

The main problems associated with DF 100 are relatively slow reaction rate for Mustard and the adjustment of pH of the DF-100 that has to be adjusted for optimal decontamination of specific chemical agents.

3.3.2 DF 200

DF 200 was developed by Sandia National Laboratories, Albuquerque, New Mexico, United States, to overcome the problems associated with DF 100 and this was found more effective on G, VX, Mustard and anthrax simulants (Diphenyl chlorophosphate, O-Ethyl S-ethyl Phenylphosphonothioate, 2-Chloroethyl phenyl sulfide and Bacillus globigii spores, respectively) by achieving 100% neutralization of all agents.

3.3.3 DS2

DS2 - Decontaminating Solution Number 2 or DS2. This solution is made up of 70% diethylenetriamine (DETA), 28% 2-methoxyethanol (also known as ethylene glycol monomethylether, EGME), and 2% NaOH. In this solution, NaOH reacts with EGME forming the ethoxide; when DETA is added to this solution, any free sodium ions are rapidly bound up by the DETA. This causes the hydroxide ions to be highly reactive, effectively increasing the strength of the basic solution.

DS2 is flammable and cannot be used in conjunction with strong oxidizing agents such as bleach, which cause it to spontaneously combust. Although DS2 is noncorrosive to most metals, it can damage paints, plastics, rubbers, and leather materials.

3.3.4 C8 microemulsion

C8 is a microemulsion formulated by the Alfred Karcher GmbH & Company in Germany as a multipurpose decontaminant reagent. The C8 emulsion consists, by weight, of 15% tetrachloroethylene (C_2Cl_4) which serves as the continuous phase, 76% water, 1% anionic surfactant, and 8% $Ca(OCl)_2$. C8 is effective in the decontamination of VX, G agents, and HD. C8 can penetrate into paint (without damaging the paint) in order to dissolve and react with chemical agents that may be imbedded inside the paint. When sprayed, C8 forms a thin, continuous film over the surface to allow for sufficient contact time in decontaminating/detoxifying the chemical agents. After decontamination, the C8 can be rinsed off with water. The drawback of C8 microemulsion is the premixing time i.e. it has to be mixed an hour prior to use to generate the emulsion.

3.3.5 M291 Kit

The M291 kit is a solid sorbent system. The kit is used to wipe bulk liquid agent from the skin and is composed of non-woven fiber pads filled with a resin mixture. The resin is made of sorptive material based on styrene/divinylbenzene and a high surface area carbonized macroreticular styrene/divinylbenzene

resin, cation-exchange sites (sulfonic acid groups), and anion-exchange sites (tetraalkylammonium hydroxide groups). The sorptive resin can absorb liquid agents and the reactive resins are intended to promote hydrolysis of the reactions.

M291 kit has drawbacks, like a black offensive dust that is unacceptable to eyes.

3.3.6 Supertropical Bleach

It is a mixture of 93% calcium hypochlorite and 7% sodium hydroxide and is more stable than bleach in longterm storage and easier to spread. Mustard gas reacts with bleach by oxidation of the sulfide to sulfoxide and sulfone and by dehydrochlorination to form compounds such as $O_2S(CHCH_2)_2$. The G agents are converted by hydrolysis to the corresponding phosphonic acids with the hypochlorite anion acting as a catalyst. In acidic solutions, VX is oxidized rapidly by bleach at the sulfur atom and dissolves by protonation at the nitrogen. On the other hand, at high pH the solubility of FX is significantly reduced and the deprotonated nitrogen is oxidized leading to consumption of greater than stoichiometric amounts of bleach.

3.3.7 Detoxifying Sponges

A reusable sponge which was made of a polymer such as polyurethane containing cross-linked complex of the plurality of enzymes (organophosphate hydrolase and acetylcholinesterase or butyrylcholinesterase) for detoxification of hazardous chemicals such as organophosphorus and/or organosulfur compounds was developed by Gordon and group. The ChE-sponges exhibit high activity and stability and are suitable for a wide variety of decontamination tasks. Once removed, OPs can then be detoxified in the enzyme-sponge pad with oxime reactivating enzyme and in so doing prevents secondary contamination⁴⁴⁻⁴⁵.

3.3.8 Nonparticulate Dry Nonwoven Pad

Ramkumar and group, developed dry nonwoven pad for chemical warfare agent decontamination. The multilayered dry pad, contains a core of activated carbon adsorbent and has capability to retain the chemical warfare agent like sulfur mustard. The nonparticulate and nonwoven dry pad physically decontaminates toxic mustard by absorbing the bulk liquid and capturing off-gassing vapors. The absorbent layers on the top and bottom of the core activated carbon layer quickly remove the bulk liquid chemical warfare agent when a pad is pressed against a surface. The middle nonwoven activated carbon core captures toxic vapors from the absorbed liquid. The surrounding absorbent layers also prevent the linting and shredding of activated carbon, thereby preventing secondary contamination⁴⁶.

3.3.9 Nanosized Metal Oxides as decontaminant

Manganese oxide nanostructures for decontamination of sulfur mustard were developed by Prasad⁴⁷, *et al.*. They found that the adsorbent composed of MnO_2 nanoaggregates is promising for the decontamination of sulfur mustard. The prepared system could destroy the agent by the pseudo first-order steady-state reaction (hydrolysis and elimination) with a half life of 9.12 h, whereas the bulk H_xMnO_2 reacts with a half

life of 29.8 h. Although, the bulk material destroys the agent, the detoxification reaction is slower than that occurring on the surface of nano aggregates. Indicating the potential of these materials for the decontamination of persistent CW agents.

3.3.10 *Cleaning Composition for Neutralising Biological and Chemical Weapons Removal Agents*

Composition for neutralization of Chemical Weapons Removal Agents, that can be used for treating and removing stains from an object and for removing residue following a clean-up after a chemical or biological weapons attack was developed by Jenevein. The composition consists of 35-45% by volume of ethanol, 1.5-2.5% by volume of isopropyl alcohol, 0.05-0.5% by volume of ethylene glycol n-hexylether, 3-4% by volume of each myristyltrimethylammonium and benzethonium chloride, 0.2% by volume of the tetrasodium salt of ethylenediamine tetraacetic acid, and 0.1-0.50 % of polyvinyl alcohol⁴⁸.

3.3.11 *Decontaminating Foams*

Decontamination foam (Decon foam) is a spray-on cleaning solution that, due to its physical properties, has a longer residence time on contaminated surfaces than regular liquids and thus provides efficient decontamination of biological and chemical contaminants (e.g. chemical warfare agents, anthrax spores or other toxic industrial materials). It is designed for use in emergency situations involving areas containing large numbers of possibly contaminated people e.g. at conventions, airports, concerts, etc.

Similarly Cronce⁴⁹, developed a Chemical warfare agent decontamination foaming composition and method this was patented by US army. The foam consists of a quaternary ammonium complex component (Benzyltrimethylammonium chloride or Benzyltriethylammonium chloride), an oxidizer (Hydrogen peroxide), a corrosion inhibitor (Isobutanolamine) and a foamer (Knockdown) with an adjusted pH of at least 8. The foam is effective in large area decontamination of the warfare agents.

Polyurethane foams: Drevon⁵⁰ & Russell⁵¹ described the incorporation of the nerve agent degrading enzyme DFPase into polyurethane foams. The activity of the DFPase in the bioplastic was shown to be limited by internal diffusion. However, some return of activity was achieved by the addition of Pluronic surfactants during the immobilization process, which brought the catalytic efficiencies up to 67% of the soluble enzyme. Thermostability assays of DFPase-polyurethanes revealed that the immobilized DFPase follows biphasic deactivation kinetics, quickly losing nearly 90% of its activity, followed by the formation of a hyperstable active form of the enzyme. This finding was supported by studying the inactivation of PEG-DFPase using circular dichroism, which suggested that the hyperstable form of the enzyme has an increased content of β -sheet.

Love⁵², *et al.* evaluated the efficacy of different decontamination formulations (solutions and foams) on indoor surfaces using bench-scale testing after exposure to the liquid chemical warfare agents sarin (GB), soman (GD),

sulfur mustard (HD), and VX. Their results suggested that the different characteristics needed for an ideal and universal decontamination technology may be incompatible in a single formulation and a strategy for decontaminating a complex facility will require a range of technologies.

Recent studies in the field of CWA decontamination

Silica Nanoparticles: Saxena⁵³, *et al.* developed silicon nanoparticles by aero-gel process and impregnated the nanoparticles with reactive chemicals like Trichloroisocyanuric acid (TCCUA), camphorylsulphonyl oxaziridine and ruthenium trichloride. Impregnated nanoparticles used to study the removal of toxic nerve and blister chemical warfare agents and their stimulants from solutions. They found as the toxicant molecule is physisorbed on impregnated silica nanoparticles it starts reacting with the active sites of the adsorbent or impregnant available on their surface. This leads to chemisorption or destruction of toxicant to such an extent that the chemical integrity of the toxicant is completely destroyed. HD, 2-HEES, 2-CEES, DECIP and GB were found to be degraded over SiO_2 + TCCUA via hydrolysis, elimination, dehydrohalogenation and oxidation reactions. Trichloroisocyanuric acid impregnated (10%, w/w) silica nanoparticles based systems can remove and detoxify CWAs into non-toxic products effectively in less time and they can be used in decontamination devices or filtration systems to remove CWAs.

Zero-valent Iron Nanoparticles: Zboril⁵⁴, *et al.* prepared nanoscale zero-valent iron (nZVI) particles and a composite containing a mixture of ferrate(VI) and ferrate(III) by thermal procedures for CWAs degradation. They achieved complete degradations of GD and VX with Fe(VI) within 10 min. They concluded that the oxidation promoted by the ferrate(VI)/(III) composite was more effective in removing CWAs than the reduction by zero-valent iron.

CuO Nanoparticle: Mahato⁵⁵, *et al.* studied decontamination reactions of persistent chemical warfare agent HD on the surface of CuO nanoparticles and found that the rate of decontamination of HD decreases with the increase on the calcinations temperature of CuO nanoparticle. Increasing the calcination temperature leads to increase in the percent of elimination products, whereas at lower calcinations temperature hydrolysis product predominates.

β -cyclodextrin derivatives as detoxifying agents: Kalakuntla⁵⁶, *et al.* synthesized new cyclodextrins based scavengers to evaluate the possibility of application of substituted cyclodextrins as potential detoxification agents. The ability of these five to detoxify nerve agents (cyclosarin, soman, tabun and VX) was evaluated by a semi-quantitative biological assay. All the modified cyclodextrins significantly decreased the inhibitory effect of chemical warfare G agents on acetylcholinesterase activity.

4. FUTURE TRENDS

In the near-future, there is a need to develop a Universal decontamination formulation that can be used against CBRN contaminants. The Universal formulation should overcome the obstacle of present technology. Another aspect that has to be kept in mind is the eco-friendliness of the system. The decontamination formulation of future has to be one that

generates bare minimum waste and keep the environment safe. It should contain highly stable active ingredients and have negligible corrosive properties. The use of micro-emulsions and nano systems with high concentration of anionic surfactants, Nanoporous materials, nanosized metal oxide aero-gels with enhanced advantages like high surface area, high reactivity, high surface-to-volume ratio towards CWA could be used.

5. CONCLUSION

There are varieties of decontamination methods available. An evaluation of several considerations will determine which specific method would be most effective and should be applied. There is no single method or product that can be applied in all situations and to all type of contaminants. Using a combination of products available at the site of incident will be the best bet to control such situation till a universal decontaminant is developed.

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