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Oxidative decontamination of chemical and biological warfare agents using L-Gel

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Abstract

A decontamination method has been developed using a single reagent that is effective both against chemical warfare (CW) and biological warfare (BW) agents. The new reagent, "L-Gel", consists of an aqueous solution of a mild commercial oxidizer, Oxone™, together with a commercial fumed silica gelling agent, Cab-O-Sil EH-5. L-Gel is non-toxic, environmentally friendly, relatively non-corrosive, maximizes contact time because of its thixotropic nature, clings to walls and ceilings, and does not harm carpets or painted surfaces. The new reagent also addresses the most demanding requirements for decontamination in the civilian sector, including availability, low maintenance, ease of application and deployment by a variety of dispersal mechanisms, minimal training and acceptable expense. Experiments to test the effectiveness of L-Gel were conducted at Lawrence Livermore National Laboratory and independently at four other locations. L-Gel was tested against all classes of chemical warfare agents and against various biological warfare agent surrogates, including spore-forming bacteria and non-virulent strains of real biological agents. Testing showed that L-Gel is as effective against chemical agents and biological materials, including spores, as the best military decontaminants.

Keywords: Biological warfare agent; Chemical warfare agent; Decontamination; Detoxification; Remediation

1. Introduction

Most previous efforts to develop decontaminating agents for chemical warfare (CW) agents have focused on military scenarios and on hydrolysis as the principal reaction [1,2]. The methods also use a preliminary high-pressure wash to eliminate most of the chemical agents before decontamination. In contrast, the present study explores acidic oxidation to facilitate hydrolysis of an agent at greater concentration, and it focuses on the decontamination of civilian facilities. The objective was to develop a single reagent and an acceptable

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decontamination method that is effective against all threats, including both CW agents and biological warfare (BW) agents [3,4]. Such an approach effectively eliminates the need for a preliminary high-pressure wash prior to decontamination.

One consequence of the terrorist events that took place on 11 September 2001, and of subsequent anthrax letters, is increased interest in decontaminating agents. Requirements for decontamination in the civilian sector are demanding and can be somewhat different than those from a military perspective [5]. Current military decontamination techniques aimed at CW agents are corrosive and can cause collateral damage to facilities and equipment. More environment friendly decontaminants are of interest for all applications.

The military requires fast action (30 min or less), whereas decontamination times on the order of several hours may be enough for the civilian sector. Rather than speed, considerations that are more important in a civilian scenario include availability of a reagent, low maintenance, ease of application, minimal training, easy deployment by a variety of dispersal mechanisms and acceptable expense. Civilian facilities will be reoccupied after decontamination for long periods and without protective equipment. Exposures to environmentally hazardous material (e.g. carcinogens) and long-term health consequences to civilian populations, including susceptible individuals, such as pregnant women or the immuno-compromised, are major concerns. Civilian decontamination must seek to minimize adverse health effects, address relevant social and political issues, and be defensible to regulatory agencies and the public. The level of decontamination required also influences the choice of decontamination systems. Understanding and influencing the answer to the

Table 1
Summary of current decontamination methods

Biological warfare agents and biotoxins	Chemical warfare agents
Liquids:	
Alcohol, ethyl	DS-2:
Alcohol, isopropyl	Diethylenetriamine (70%)
Alcohol, isopropyl + 5% propylene oxide	Diethylene glycol monomethyl ether (28%)
Glutaraldehyde	Sodium hydroxide (2%)
Hydrogen peroxide, aqueous	Household bleach (5%)
Phenol	Supertopical bleach (>5%)
Soap and water	HTH: calcium hypochlorite
Sodium hypochlorite	Soap and water
Virkon S^{TM} (Antex Corporation)	Sodium carbonate
	Sodium hydroxide
	Water
Gases and vapors:	
Ethylene oxide	None
Paraformaldehyde	
Steam	
Hydrogen peroxide, vapor phase	
Physical agents (energy sources):	
Cobalt 60	Incineration
Heat	
Ultraviolet light	
X-rays	

question: "How clean is clean enough?" is key [6]. It would be deceiving, for instance, to imply that 100% of an agent is destroyed if the level of detection during sampling and analysis is only one part in a hundred thousand. Even though future studies need to resolve all these issues, the present investigation focused on the immediate problem of developing an effective decontamination reagent and application method that can be currently deployed.

The research and development efforts were focused on developing a single, non-toxic and non-corrosive decontamination system for all CW and BW agents. Rather than complete destruction, the detoxification or degradation of CW and BW agents to non-toxic and environmentally acceptable components was evaluated. Another focus was on developing an easy-to-use and readily deployable decontamination system for use by first responders, as well as specialized decontamination teams working in different scenarios.

Three types of civilian scenarios in which an incident could potentially occur were considered. They are an outdoor scenario such as a stadium, a semi-enclosed scenario such as a subway, and an enclosed scenario such as an office. Methods for use on interior surfaces can have different requirements than those appropriate for outdoor use, where natural attenuation over time might be adequate in certain cases. Table 1 lists the decontamination methods currently used for BW and CW agents.

2. Oxidant selection

Many kinetic and mechanistic studies have been done on the G-type chemical agents, which include Tabun (GA), Sarin (GB) and Soman (GD). Hydrolysis in basic media works well for these agents, but less well with Sulfur mustard (H or HD). Direct base hydrolysis is not effective for V agents, an example of which is VX. However, oxidation of the sulfur in VX in aqueous acid medium is rapidly followed by hydrolysis to non-toxic products. An acidic medium also causes protonation of the amine nitrogen, both increasing the solubility of VX and enhancing the oxidation on sulfur.

The initial selection process focused on aqueous acidic oxidation with simultaneous hydrolysis of a chemical agent to achieve decontamination. The choice of oxidation as an approach to the detoxification of chemical agents is a result, in large part, of work performed over many years at the Edgewood Chemical Biological Center (ECBC) [7–9]. The acidic oxidation mechanism was also investigated to determine the effectiveness for destroying live biological agent organisms and spores [10,11]. BW agents, especially spore-forming bacteria, are extremely difficult to kill. A strong oxidizer in a low-pH solution (<2) oxidizes the thiol groups in proteins and enzymes. It also forms free hydroxyl radicals, which can cause DNA and RNA strand breakage. Thus, a strong acidic oxidizer includes two key mechanisms with the potential to destroy BW agents.

All work performed at Lawrence Livermore National Laboratory (LLNL) on decontamination of CW and BW agents was done using surrogates rather than the real agents. Therefore, during all initial experiments, the surrogates were selected to replicate as closely as possible those properties of the real agent that are important to decontamination. Table 2 shows the chemical and biological agent surrogates used in oxidation/hydrolysis experiments conducted at LLNL. Real CW agents were subsequently used in laboratory and field studies conducted offsite and independently by other agencies. BW surrogates included

Table 2
Real CW and BW agents and surrogates used for testing

Chemical agent	Chemical agent surrogate
Sulfur mustard (H or HD)	Chloroethyl ethyl sulfide (CEES)
G agent (Sarin or GB)	Diphenyl chlorophosphate (DPCP)
V agent (VX)	Amiton
Biological agent	**Biological agent surrogate**
Anthrax	*B. subtilus* var. *niger* (BG) spores Gram positive and spore-forming bacteria Durable spore common in certain soils, non-virulent Easily grown in culture, easily detected
Plague (Bubonic)	*Pantoea herbicola* Vegetative, non-spore forming, gram-negative bacteria Non-virulent, found on plant leaves Easily grown in culture, easily detected
Botulinum toxin	Ovalbumin (tested in gels only, not in field tests) High-molecular-weight protein Benign and non-toxic

the spore-forming bacterium *Bacillus subtilis* var. *niger*, also known as *B. globigii* (BG), because such spores are difficult to kill. In the subsequent tests, approval was obtained to use strains of the real biological agents *B. anthracis* (Sterne) and *Yersinia pestis* (strain D27). These strains are rendered non-virulent and can be experimentally studied because their complete genome is known, and they do not contain the toxic plasmids that are present in the real BW agents.

In all, 12 oxidants listed in Table 3 were initially evaluated in the laboratory against CW surrogates (DPCP, CEES and Amiton) and then against BW surrogates (spores, vegetative bacteria and proteins). The goal was to find the most effective decontamination agent at the lowest effective concentration. Testing was typically conducted in triplicate with controls and blanks, and 7–9 oxidants listed in Table 3 were tested against most surrogates and evaluated for efficacy.

Table 3
Oxidants evaluated against CW and BW surrogates

Sodium hypochlorite (positive control)
Hydrogen peroxide
Potassium permanganate
Classic Fenton's reagent (3% hydrogen peroxide, 10 ppm $CuSO_4$ at pH = 3)
Los Alamos reagent (5% $CuCl_2$, 1% ascorbic acid, KCl and HCl buffer at pH = 2)
Cupric chloride (5%)
Peroxydisulfate
DOW™ liquid (foam) bathroom cleaner
Virkon S™ (evaluated for BW only)
Potassium peroxymonosulfate + copper ion (10 ppm $CuSO_4$)
Potassium peroxymonosulfate + surfactant (Snoop™; evaluated for BW only)
Potassium peroxymonosulfate (Oxone™)

Table 4
Oxidation of chloroethyl ethylsulfide (CEES)

Oxidizer[a]	Reaction time (min)	Percent oxidized
Sodium hypochlorite	30	91
H_2O_2 (Fenton's reagent)	30	100
Ammonium peroxydisulfate	10	40
	30	100
Potassium peroxymonosulfate (Oxone)	10	100
	30	100

[a] All reactions were performed at pH = 3, except for sodium hypochlorite at pH = 12. The ratio of oxidizer to CEES was 2.

2.1. Methods

Initial oxidation of CW surrogates began with preparation of oxidizers in deionized water to a 0.3N concentration and adjustment with sulfuric acid to pH = 3. After the addition of 0.5 μl of surrogate to 15 ml vials containing the oxidizer solution, vials were placed on a shaker for 30 min. Reactions were then quenched with 10 ml of methylene chloride, and samples were analyzed by gas chromatography and mass spectrometry (GC–MS) using a Saturn Ion Trap instrument with a DB-5ms column.

Initial screening for oxidation of BW agent simulants began with dilution of the BG spore culture to $\sim 5 \times 10^8$ cells/ml. Eppendorf tubes containing 0.1–1 ml aliquots of spores were tested for 30 min with oxidizing reagent at normalities ranging from 0.015 to 3. Cells were spun in a microfuge, rinsed in appropriate media two times and resuspended in fresh nutrient broth. Serial dilutions were prepared using appropriate media as diluent and 100 μl of each diluent was plated in duplicate on nutrient agar and incubated at 30 °C for 24 h. The number of colonies per plate was then visually counted.

2.2. Results

Results for the oxidation of CEES are shown in Table 4; results for the oxidation of Amiton are shown in Table 5. These initial laboratory oxidation experiments on CW surrogates demonstrated that potassium peroxymonosulfate effectively destroys Amiton (>99%

Table 5
Oxidation of amiton

Oxidizer[a]	Reaction time (min)	Percent oxidized
Sodium hypochlorite	30	30
H_2O_2 (Fenton's reagent)	30	0
Ammonium peroxydisulfate	10	20
	30	90
Potassium peroxymonosulfate (Oxone)	10	20
	30	93
	40	>99

[a] All reactions were performed at pH = 3, except for sodium hypochlorite at pH = 12.

oxidized after 40 min) and CEES (100% oxidized after 30 min). Initial testing of the G agent surrogate DPCP resulted in 100% destruction. However, it was later discovered that DPCP also decomposes when exposed to untreated glass surfaces in the presence of moisture. This observation proved to be advantageous when it was shown in subsequent testing that the silica gelling agent in fact catalyzed the decomposition of DPCP and actual G agents. The initial screening oxidation experiments against BW agent simulants yielded results that were very similar to those for CEES and Amiton, further supporting the effectiveness of potassium peroxymonosulfate.

The initial laboratory tests of oxidants, together with environmental and practical considerations, led to the selection of Oxone^{TM}, whose active ingredient is potassium peroxymonosulfate. This commercial product is manufactured by DuPont and has the chemical formulation $2KHSO_5 \cdot KHSO_4 \cdot K_2SO_4$.

3. Selection of gelling agent

The focus of this investigation was on the decontamination of civilian facilities, including building interiors. It is unlikely that spraying only water-based solutions of decontaminants would be effective in all cases. Consequently, carriers were investigated that would increase the contact time between the contaminant and decontaminating agent and would cling to walls and ceilings. Aqueous foams and gelled aqueous solutions were assessed.

Results of experiments showed conclusively that organic-based foam components would not have long-term compatibility with oxidizing agents. Gelation using fumed silica was selected for many reasons. Thixotropic gels tend not to sag or flow down the walls or off ceilings. Silicon dioxide colloidal particles are commercially available and do not require special preparation. The inert characteristics of the particles allow them to survive in strong oxidizing solutions and to undergo no reactions that would degrade the oxidant. Such gels lend themselves to simple delivery systems, such as Simplex sprayers or air-assisted sprayers. Such gels may, because of the surface characteristics of fumed silica, be able to absorb certain of the chemical or biological agents (or embed spores into the gel) or to catalyze the decomposition of certain chemical agents. Once the decontamination process is complete, such gels can easily be cleaned up by vacuum or wiping with a damp cloth. For outdoor application, no cleanup is necessary.

The evaluation of various gelling agents led to the selection of Cab-O-Sil EH-5 fumed silica as the gelling agent of choice. In addition, this material was selected because it is non-toxic when inhaled. The successfully developed gel formulation has been named “L-Gel”. L-Gel-115, for example is a formulation of 1.0N aqueous Oxone solution gelled with 15% EH-5.

4. Application of L-Gel

L-Gel can be easily liquefied by mechanical shaking or stirring. Attempts were made to spray the liquefied gel using a commercial paint sprayer. Both airless and compressed air sprayers have been successfully employed.

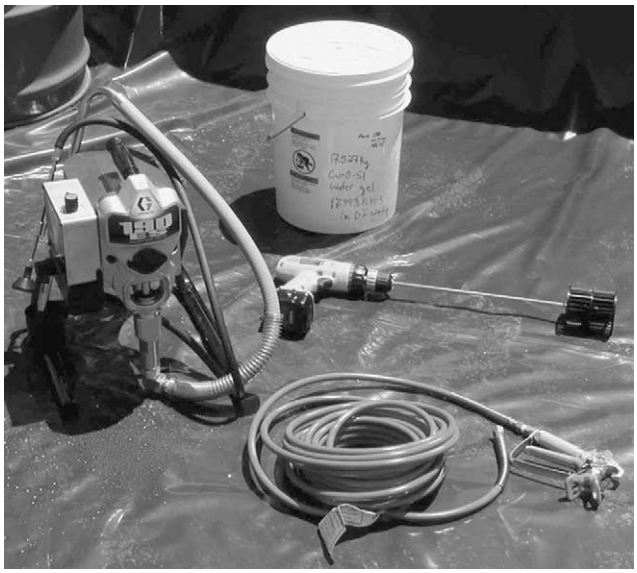

Fig. 1. Commercially available equipment suitable for L-Gel application includes a Graco Airless Electric Paint Sprayer.

The current concept of operation begins with a container of premixed L-Gel in the form of a convenient and transportable, high-viscosity, gelatin-like material that does not easily spill. The container is equipped with a mechanical stirrer so that the gel can be liquefied immediately before use. The gel can then be sprayed using essentially any type of commercial spray device with just about any type of atomizing nozzle. For example, an airless Wagner Power Painter (hand-held model) has been used for smaller applications, or a Graco Electric Airless Paint Sprayer (model XR7 on wheels, Fig. 1) or equivalent has been used for larger applications (∼5 gal). Stainless-steel nozzles are recommended because the acidic gel is corrosive to certain nozzle metals. During the development stage, testing of water formulations containing 12.8–25% EH-5 showed that a broad range of Cab-O-Sil EH-5 concentrations can be sprayed.

5. Laboratory testing on substrates

Prior to independent field tests conducted offsite, a series of gelled oxidation experiments was performed at LLNL using CW and BW surrogates on several test substrates that would be expected in an actual decontamination scenario. The principal methods and findings for decontamination against CW surrogates and BW spores on substrates are summarized here.

5.1. Methods

Peroxymonosulfate in gel (0.8N) was tested for decontamination against CW surrogates—Amiton, DPCP, and CEES—to investigate its effectiveness on real surfaces. Test substrates

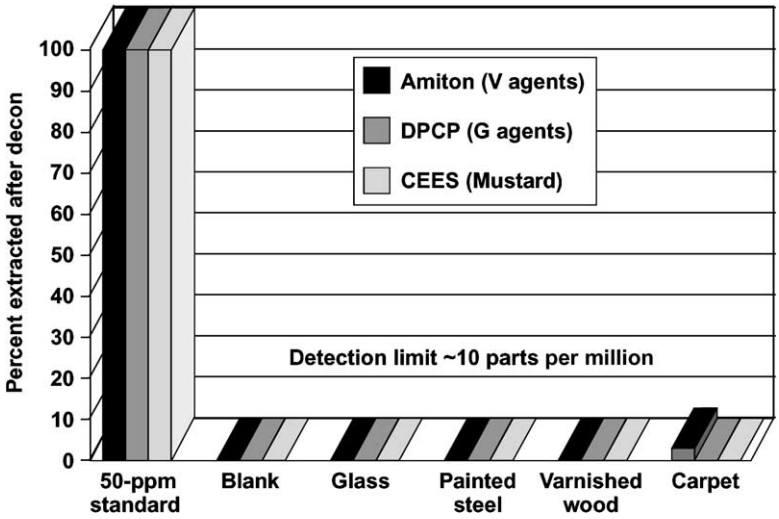

Fig. 2. Percent of extracted CW agent from substrates after decontamination, using GC–MS detection methods.

included glass, fiberglass, varnished wood, acrylic painted steel and carpet. A surrogate (2.5 μl) was applied to individual samples of the test material that were approximately 1 cm^2 in size, and the reagent gel (1.0 ml) was applied to the surface of the material with a syringe. Contact time of the reagent ranged from 30 min to complete dryness prior to rinsing. The percent of extracted CW agent from substrates after decontamination was

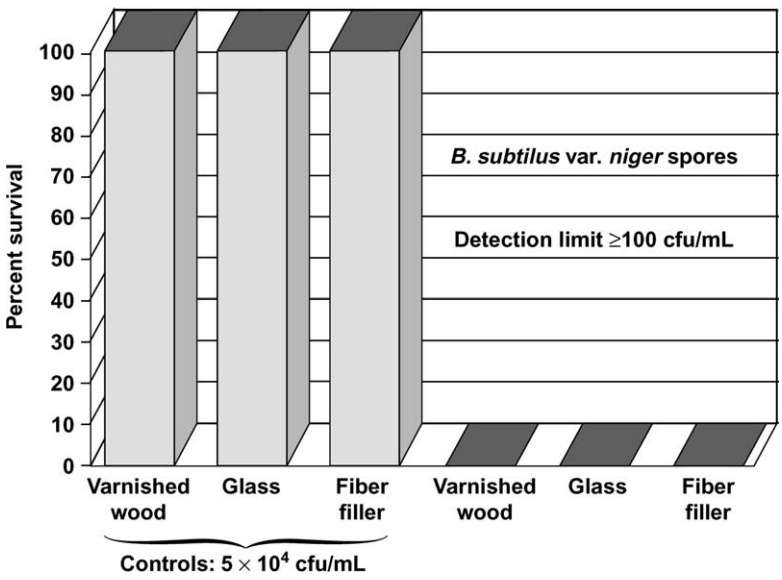

Fig. 3. Percent survival of BG spores from three substrates after decontamination.

obtained by GC–MS using a Saturn Ion Trap instrument with a DB-5ms column. All experiments included appropriate laboratory controls (water/gel) and standards. The gel was then laboratory tested on the similar substrates and in similar concentration-dependent studies for biocidal activity against *B. subtilus* var. *niger* (BG) spores and non-virulent strains of live *B. anthracis* spores (Sterne) and *Y. pestis* (strain D27). Reactions were quenched with 100 mM sodium thiosulfate, and material was washed three times with potassium phosphate. Spores were plated on nutrient agar and incubated at 30 °C for 24 h. Colonies were visually counted.

5.2. Results

Fig. 2 shows that for decontamination against CW surrogates, the L-Gel system was 100% effective on all tested substrate materials (glass, painted steel, varnished wood, and carpet) except for Amiton on carpet, where the L-Gel system was 95% effective. Fig. 3 shows that the L-Gel system was 100% effective in the laboratory tests against BG spores on varnished wood, glass, and fiber filler.

6. Independent laboratory and field testing

Following its demonstrated effectiveness against surrogates for all classes of chemical agents, L-Gel was tested against real chemical agents. Chemical agent testing was performed independently at three locations:

- field testing at the Military Technical Institute of Protection, Brno, the Czech Republic (October 1998);
- lab testing at Edgewood Chemical Biological Forensic Analytical Center (ECBC), Aberdeen Proving Ground, MD (November 1999);
- lab testing with thickened agents at the Defence Evaluation and Research Agency (DERA), Porton Down, UK (October 1999).

Following the laboratory-demonstrated effectiveness of L-Gel against surrogate spore-forming bacteria, L-Gel was tested against BG in two field exercises. In December 1999, LLNL participated in BW field tests conducted by the Soldiers Biological and Chemical Command at the US Army Dugway Proving Ground, West Desert Test Center, UT, USA. The test objectives were to compare the ability of several candidate decontamination materials to inactivate a BW agent stimulant. In October 2000, LLNL participated in a BW agent room-decontamination exercise at Dugway Proving Ground where selected decontamination methods were tested in full-scale mock office spaces.

6.1. Methods

Offsite testing methods were determined by the agency hosting the trials. Different tests and locations evaluated various decontaminants and methods in addition to L-Gel. This section summarizes the principal methods, as reported by testing agency, for selected but representative L-Gel results reported in this article.

6.1.1. CW agent tests in the Czech Republic

Various proprietary decontaminants, including L-Gel-115 and a water solution of calcium hypochlorite (HTH, a standard military decontaminant serving as a baseline), were tested outdoors on substrates against chemical agents VX and GD. Sample substrates were aged concrete, new concrete, aged asphalt and new asphalt. Aged materials were more than 20 years old. VX was only tested on new materials. The agent was deposited on a circular area of $\sim$20 m^2 using a hand sprayer at an areal density of $\sim$15 g/m^2. Samples to be analyzed were 25 cm^2 in area, collected from the outer circumference of the circular area. A set of samples was removed immediately after deposition for chemical analysis to determine actual spray density. After $\sim$2 h elapsed, a second set of samples was collected for analysis to determine the amount of agent present at the time of decontamination. Each decontaminant was sprayed on $\sim$5 m^2 of contaminated surface and remained in contact for 30 min before sample collection. Samples were washed in the laboratory with distilled water, placed in a stainless-steel cuvette, and extracted for 15 min with isopropanol in an ultrasonic bath. Residual bioactivity was analyzed spectroscopically to determine relative effectiveness.

6.1.2. CW agent tests at the ECBC

Studies included panel tests on various substrate surfaces. Sample substrates were the same as the polyurethane painted oak, acrylic painted steel, and indoor–outdoor carpet materials that were used in surrogate testing at LLNL. The CW agent (2.5 μl) was placed on the sample substrate and allowed to stand for 15 min. A 1.0 g aliquot of L-Gel was placed on the sample and allowed to dry for about 24 h. The entire sample was extracted with 10 ml of methylene chloride and analyzed by GC and flame photometric detector (FPD), the latter for sulfur and phosphorous detection. Experiments were performed in triplicate. Estimated detection limits were GD = 0.1 μg/ml, HD = 1.0 μg/ml, and VX = 0.1 μg/ml.

6.1.3. CW agent tests at Porton Down

Thickened GD (TGD) and thickened mustard (THD) were applied to $\sim$3 in. × 5 in. metal plates painted with either alkyd paint or a polyurethane paint. Agents remained in contact with the surfaces for 1 h. L-Gel-115 was then sprayed on samples in the vertical position, using a commercial British compressed air paint sprayer. After a contact time of 30 min, sample panels were sprayed with ambient-temperature water at high pressure. Panels were placed in a measured amount of isopropanol for 2 h, and the extract was analyzed by GC–MS.

6.1.4. BW panel field tests at Dugway Proving Ground

Test panels, prepared in triplicate, were acoustic ceiling tile, commercial carpet, fabric-covered office partition panels, smooth painted wallboard, concrete block, and steel test panels painted with Army/Marine chemical agent resistant coating (CARC). The BG solution used on test panels was produced from dry powder (10^{11} spores/mg) suspended in 1:100 buffer solution. BG was applied to vertically suspended test panels (except concrete block) via a Badger Airbrush 100CL directed from a distance of 0.46 m. The nozzle sprayed a fine mist perpendicular to the panel surface. The target value for BG deposition density was 10^8 to 10^9 colony forming units (cfu) per sample area. Size of the sampled area was 10.16 cm^2. Decontaminating agent L-Gel-115 was applied and left overnight. Panels were sampled

using swabs at three random locations to determine baseline contamination. The decontamination reaction was quenched with 20 ml phosphate buffered saline (PBS) containing 0.1 TritonX 100 and 100 mM sodium thiosulfate. Samples were placed on a shaker for 10 min. Spore suspension was serially diluted in a sequence between 10^0 and 10^6. A 0.2 ml volume of diluent was delivered to each plate and spread using standard techniques. Spore population was quantified by culturing, in triplicate, on Trypticase™ Soy Agar (TSA). Plates were incubated at 37 °C for 24 h, then counted visually by trained personnel.

6.1.5. BW room decontamination at Dugway Proving Ground

Six 8-ft-square mock offices were built in an abandoned building. The flooring was divided into quarters, and consisted of carpet, vinyl tile, oak flooring and painted concrete. Walls consisted of stucco, wood paneling, sheet rock and carpet. The ceiling was suspended ceiling tile. Each room was contaminated with 4 g of BG by a simulated explosion using a disseminator; spores were distributed by an oscillating fan. Approximately 400 samples were collected by swabs from multiple locations, one sample per square foot. Swabs were quenched in sterile, buffered solution containing sodium thiosulfate. Diluent was plated onto TSA agar, and live colonies were counted. Detection limit of the analyses was 1×10^2 cfu per 4 in.^{2}.

6.2. Results and discussion

Fig. 4 shows the results of field tests in the Czech Republic using chemical agents VX and GD. L-Gel was as effective—or in most cases, more effective—against VX and GD

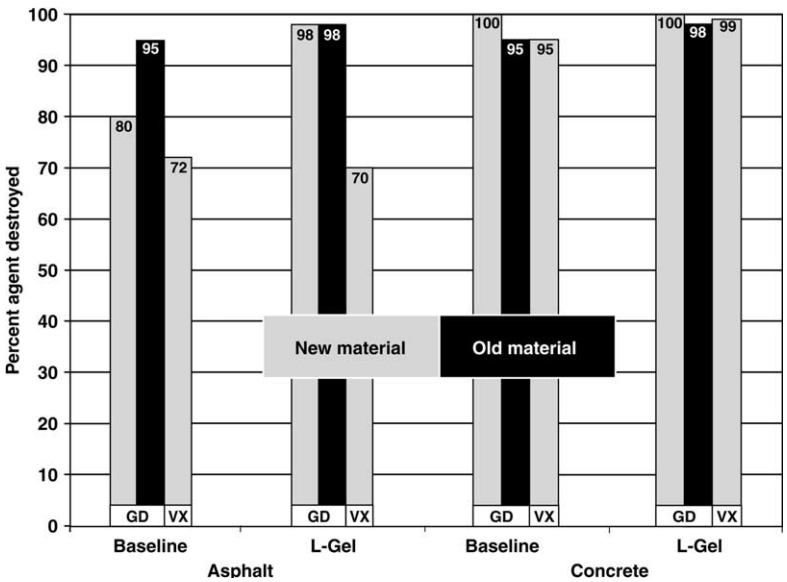

Fig. 4. Field testing with real CW agents on concrete and asphalt substrates showed that the L-Gel system was as effective or more effective against VX and GD than the baseline US military method using HTH. VX was only tested on new materials.

Table 6
Results of thickened agent decontamination tests with L-Gel-115

Thickened agent	Alkyd paint	Polyurethane paint
TGD	35% destroyed	64% destroyed
THD	50% destroyed	66% destroyed

after a 30 min decontamination time than the baseline Czech military method using calcium hypochlorite (HTH).

The ECBC tests using VX, GD and HD on small samples of acrylic painted metal, polyurethane varnished oak and indoor–outdoor carpet showed that the chemical agents were completely destroyed by L-Gel-115, except for minor amounts of GD on the two painted surfaces. For the polyurethane surface, only 6% of the GD was recovered; for the acrylic surface, only 20% of the GD was recovered. This result is not unexpected. The problem is the adsorption of GD in paint and the inability to completely hydrolyze GD with a single application of L-Gel. However, if application of the decontaminating agent is repeated several times, the problem is eliminated.

Military interest in evaluating L-Gel against gelled chemical agents led to the testing at the DERA, Porton Down, UK. Table 6 summarizes the results, which showed that the L-Gel-115 formulation was not as effective as desired because of a problem of extracting the agent from the polymer matrix in the time required by military operations (reaction time for L-Gel-115 was 30 min in the Porton Down tests). Further

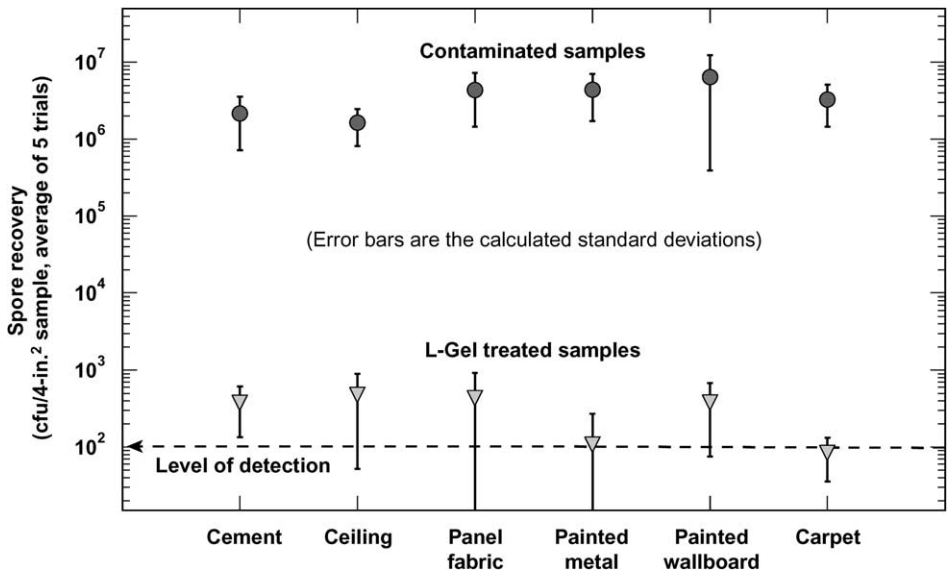

Fig. 5. Results of field tests on six materials contaminated with BG spores before and after application of L-Gel. BG spores were reduced by an average of 99.988% by L-Gel.

development will be required if L-Gel is to be considered for military application, and to evaluate the potential of a co-solvent to eliminate the problem with gelled chemical agents.

Results for the BW agent field experiments conducted at Dugway are shown in Fig. 5. Live BG spores on six different types of test panels were reduced by an average of 99.988% through the application of L-Gel-115. Finally, in the full-scale room-decontamination field tests at Dugway, the performance of L-Gel was comparable to that of the paraformaldehyde standard in eliminating BG from the mock office. More bacteria were found on the floor than on any other surface. Both paraformaldehyde and L-Gel reduced the distribution of BG on the floor by about five orders of magnitude. L-Gel did not bleach or damage office surfaces, with the exception of some rust on ceiling supports.

7. Conclusions

Our research shows that L-Gel is effective against all chemical and biological agents. The fumed silica gel is compatible with strong oxidizing agents, and the system is relatively non-corrosive, with a pH approximately equal to that of vinegar or lemon juice. The L-Gel system is relatively inexpensive ($\sim$US$ 1.00/m^2) and available.

L-Gel maximizes contact time because of its thixotropic nature. L-Gel clings to walls and ceilings and does not harm carpets or painted surfaces. The ability of L-Gel to liquefy when stirred or shaken and to return to the "solidified" state upon standing enhances material handling, application and contact time.

Methods of dispersal are easy and can be varied depending on user needs and required viscosity (200 g/m^2 at a thickness of $\sim$5 mil). No complicated equipment is required for preparation or application. L-Gel can be sprayed using a commercially available sprayer and stainless-steel atomizing nozzle. Drying time is 1–6 h; decontamination is faster, typically 30–40 min. Dried residue indoors can be vacuumed and discarded. Outdoor use requires no cleanup. US EPA methods (8260/8270 for volatiles and semi-volatiles) show residual byproducts to be non-hazardous.

L-Gel is expected to have a long shelf life (>1 year) if not opened, allowing it to be pre-mixed. L-Gel material meets non-hazardous/non-corrosive requirements of the Department of Transportation and is stable during shipping.

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