



Efficacy of liquid and foam decontamination technologies for chemical warfare agents on indoor surfaces

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ABSTRACT

Bench-scale testing was used to evaluate the efficacy of four decontamination formulations on typical indoor surfaces following exposure to the liquid chemical warfare agents sarin (GB), soman (GD), sulfur mustard (HD), and VX. Residual surface contamination on coupons was periodically measured for up to 24 h after applying one of four selected decontamination technologies [0.5% bleach solution with trisodium phosphate, Allen Vanguard Surface Decontamination Foam (SDFTM), U.S. military Decon GreenTM, and Modex Inc. and EnviroFoam Technologies Sandia Decontamination Foam (DF-200)]. All decontamination technologies tested, except for the bleach solution, performed well on nonporous and nonpermeable glass and stainless-steel surfaces. However, chemical agent residual contamination typically remained on porous and permeable surfaces, especially for the more persistent agents, HD and VX. Solvent-based Decon GreenTM performed better than aqueous-based bleach or foams on polymeric surfaces, possibly because the solvent is able to penetrate the polymer matrix. Bleach and foams out-performed Decon Green for penetrating the highly polar concrete surface. Results suggest 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.

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1. Introduction

Implementing an efficient remediation and recovery process after a civilian facility is contaminated with a chemical warfare agent (CWA) requires understanding the efficacy of a range of decontamination technologies. Many liquid and foam decontaminants have been developed to address the decontamination needs and performance criteria for military operations [1,2]. Far less is known about the performance of such technologies for application to civilian infrastructure [3]. Even trace amounts of residual chemical contamination may prove unacceptable in civilian settings [4,5].

As part of an effort funded by the U.S. Department of Homeland Security to improve the nation's preparedness for indoor facility restoration after a CWA release, four liquid and foam

decontamination technologies for typical indoor surfaces were evaluated experimentally for efficacy against GB, GD, HD, and VX contamination. The U.S. Environmental Protection Agency has evaluated separately the efficacy of other technologies, principally fumigation, for decontaminating CWAs on typical indoor surfaces [6–8].

Although it was anticipated that each of the decontamination technologies tested as part of the present investigation would have some efficacy under the conditions for which it was designed, it is important to compare and quantify the efficacy of each technology as part of an effort to develop an effective overall decontamination strategy for civilian applications. The results of decontamination efficacy are typically reported in two ways: (1) by a commercial vendor through marketing material, which often does not contain the level of experimental detail necessary to evaluate the validity of efficacy claims, or (2) in military reports that describe efficacy in terms of meeting military criteria. Many efficacy evaluations are not performed on target chemicals themselves but, rather, on chemical surrogates [9,10] that may have limited ability to mimic all the important physico-chemical properties of target chemicals. In addition, previous decontamination efficacy testing [11] is often performed on the simplest of substrates, namely nonporous and

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nonpermeable surfaces, where the CWA resides as a free liquid on the surface instead of being bound physically or chemically by the surface. Furthermore, because no experimental data are available that compare the performance of different liquid and foam decontamination technologies using similar testing protocols, the relative performance among existing technologies is not known.

Surface decontamination technologies require contact between an active decontamination component and a CWA. If the kinetics of a reaction with a CWA are slow, or there are mass-transport limitations, increasing the contact time may increase the overall decontamination performance. Decontamination foams or gels [12] cling to surfaces and are designed to increase the contact time of the decontamination technology on the surface compared to liquid formulations that rapidly run off some surfaces, such as vertical walls and ceilings. Although numerous decontamination technologies are in development, the current availability of a particular technology is also a critical operational consideration when rapid facility decontamination and restoration are paramount.

The four surface decontamination technologies evaluated in this study were chosen to span a range of available technology characteristics. Bleach (sodium hypochlorite) is a strong oxidizing aqueous solution that has widespread availability and a long history of use in CWA decontamination [8]. Liquid bleach does not have good contact time on vertical walls or ceilings, thus typical decontamination operations with bleach employ bleach scrubbing or multiple applications. Bleach is highly corrosive and should not be applied to sensitive electronic equipment intended for reuse. Two commercially available, aqueous-based, oxidizing foams were tested. The Allen Vanguard Surface Decontamination Foam (SDF™) formulation, which is a member of the foam family based on the Canadian Aqueous System for Chemical/Biological Agent Decontamination (CASCAD™), is specifically designed for building decontamination. Sandia Decontamination Foam (DF-200) is available from Modec Inc. and EnviroFoam Technologies. Both of these foam decontamination technologies feature a less aggressive oxidation technology, compared to bleach, and both result in better corrosion prevention. The fourth surface decontamination technology tested is the latest U.S. military liquid formulation, Decon Green™, which represents a solvent-based decontamination technology in contrast with aqueous-based technologies. Decon Green™ is not commercially available, but has been licensed to Strategic Technologies Enterprises, Inc. (STE), a subsidiary of STERIS Corp. Although corrosion concerns for solvent-based liquid decontamination technologies are minimal, potential materials-compatibility issues with plastics and polymers may prevent the reuse of such materials after decontamination.

2. Experimental

2.1. Agent synthesis

Neat liquids of four CWAs were synthesized at Lawrence Livermore National Laboratory (LLNL): (1) sarin, (GB, isopropyl methylphosphonofluoridate); (2) soman, (GD, pinacolyl methylphosphonofluoridate); (3) sulfur mustard, (HD, bis (2-chloroethyl) sulfide); and (4) VX, (O-ethyl S-[2-(diisopropylamino)ethyl] methylphosphonothioate). The purity of each of the four CWAs was verified to be >97% using gas chromatography–mass spectrometry (GC–MS) analysis.

International treaties regulate possession of highly toxic chemical warfare agents, and handling is only permitted in laboratories approved for CWAs under strict scrutiny. All work was performed through the Forensic Science Center and Lawrence Livermore National Laboratory, which has the authority and capability to synthesize and safely handle small quantities of CWAs. All experiments were conducted in triplicate, using standard scientific QA

procedures, including positive and negative controls and routine instrument calibrations.

2.2. Indoor materials

Materials chosen for exposure to CWAs were selected from a range of typical indoor surfaces. Common materials that are easily removable (e.g., carpeting, acoustic ceiling tiles, and furniture) were not considered. Materials purchased and used as-is for the evaluation were stainless-steel coupons made from 1/16-in.-thick (~1.56-mm) sheets of 304 stainless steel; vinyl floor tile [Armstrong commercial flooring, Standard Excelon vinyl composition tiles, Pattern 51858, Imperial Texture, sandrift white, 1/8-in. (3.175-mm) thick]; latex-painted drywall [standard 0.438-in. (11.1-mm) dry-wall painted with 1 coat of Glidden commercial latex primer and 1 coat of interior eggshell paint]; and glass (Gold Seal Microslides, Becton Dickinson and Co., soda-lime microscope slide glass, pre-cleaned, ground polished edges, plain). Concrete coupons were made at LLNL from a water and Portland cement mass ratio commonly used in construction (0.485:1.0), but made lean in sand (sand to cement ratio=3, instead of 5–6) to be workable and to avoid extensive entrapped air in the cast coupons (35-mm diam, 17-mm thick). Portland cement type I/II (Quikrete brand) was used with a well-graded sand aggregate from U.S. Silica (ASTM 20/30, C-778), with 98% of the particles between 600 and 850 μm (20 and 30 mesh). Because the reactivity of newly cured concrete with CWA may not be representative of most concrete in facilities [13], concrete coupons were rapidly aged in a 25% CO₂ atmosphere for 2 weeks to reduce the reactivity through carbonation, the same mechanism by which concrete naturally reduces its reactivity, albeit more slowly. Other than the cast concrete coupons, all other materials for chamber exposure were cut into pieces, with top surface areas ranging from approximately 2 to 10 cm².

2.3. Preparation of decontamination technologies

All decontamination technologies were prepared immediately prior to surface application. The liquid bleach decontamination formulation was prepared by diluting Clorox® regular bleach (5% by mass sodium hypochlorite) with Milli-Q water in a 1:9 ratio to create a 0.5% by mass sodium hypochlorite solution. Trisodium phosphate was added as a surface wetting agent so that the final decontamination solution contained 0.0625% by mass of trisodium phosphate.

Decon Green™ was prepared in 100-mL batches according to the formulation described in U.S. military reports [11], namely 60% propylene carbonate, 10% aqueous H₂O₂, 10% triton X-100, 2.07 g K₂CO₃, and 0.48 g K₂MoO₄.

Easy Decon™ DF-200 foam was purchased and prepared in a 2-L beaker by mixing the 3-part formulation in the same ratios as those specified by the manufacturer. Initially, 95 mL each of Part 1 “Penetrator,” containing quaternary ammonium compounds and benzyl-C12–C16 alkyl di-methyl chlorides, and Part 2 “Fortifier,” containing liquid hydrogen peroxide, were mixed well. Then, 4 mL of Part 3 “Fortifier Booster,” containing diacetin, was added, and a Cuisinart hand blender was used to create the decontamination foam.

SDF™ Foam was purchased and prepared according to the manufacturer's directions for the multicomponent formulation. Thus, 1.8 g of GPB-2100 dry-powder buffer component was rinsed using Milli-Q water into a 50-mL cylinder. Then 4.5 mL of GCE-2000 surfactant or foaming agent component was added to the graduated cylinder, and the total volume in the graduated cylinder was increased to 50 mL with Milli-Q water. A micro stir-bar was used to mix until dissolved. Separately, 7.8 g of GP-2100 dry-powder decontaminant component was dissolved in Milli-Q water and

brought to a volume of 50 mL. The two solutions were combined and brought to a final volume of 150 mL with the addition of Milli-Q water. The 150 mL of solution was then blended in a Waring Blender (TD-WB-000) with special impeller (TD-WB-001) for 2–3 s to create the decontamination foam.

2.4. Liquid agent exposure

Each CWA was applied to coupons as 5 separate 200-nL neat drops evenly spaced over the surface using a 2.5- μ L pipette. The only exception was concrete coupons, which required that a larger amount of HD (5 separate 1.2- μ L droplets) be applied to the surface to be measurable after surface reactivity occurred. Contaminated coupons were then placed on a vertical stainless-steel rack within a polished stainless-steel chamber to ensure realistic contact time of CWA with the various coupon surfaces before decontamination was initiated. These times were chosen based on the observed penetrating ability and persistence of agents on the surfaces. Clean air flowing into the chamber at 22 °C and 11% relative humidity was controlled using a mass flow controller (150 mL/min) that resulted in an air exchange rate in the chamber of approximately 5 air volumes per hour. Vapor exiting the chamber was bubbled through 5% bleach (sodium hypochlorite) to decontaminate any CWA in the vapor exhaust.

At various times for up to 1 week, the chamber was opened, and coupons were removed for decontamination testing. Liquid GB was allowed to remain on the concrete surface for 1 h and on latex-painted wallboard and vinyl floor tile surfaces for 24 h. No quantifiable GB was found on glass or stainless steel after 1 h following droplet deposition. Liquid HD was allowed to remain on the surface of glass, stainless steel, and concrete for 2 h, and it remained on the surface of latex-painted wallboard and vinyl floor tile for 1 week. Liquid GD was allowed to remain on the surface of glass for 30 min, concrete for 2 h, and vinyl tile and wallboard for 6 h. Liquid VX was allowed to remain on the surface of glass, stainless steel, and concrete for 24 h. VX remained on the surface of latex-painted wallboard and vinyl floor tile for 1 week. Given the different quantity of agent applied, persistence, volatility, and aging time, the beginning concentration of agent varies with each experiment.

2.5. Application of decontamination technologies

For each combination of CWA and coupon surface, and at each predetermined elapsed time, 3 contaminated coupons were extracted without decontamination for analysis to determine recoverable contamination levels after the allotted CWA contact times. In all, a total of 60 no-treatment controls were evaluated (i.e., 4 CWA types tested \times 5 coupon types \times 3 coupons for each combination). The remaining contaminated coupons were placed in individual 2-oz jars for application of a selected decontamination technology. Liquid decontamination technologies were applied to horizontal coupons using a spray bottle with an adjustable nozzle that disseminated liquid as a mist until the surface was completely covered. Foam decontamination technologies were applied to horizontal coupons using a spatula to spread a 2–4-mm coating over the entire surface. Immediately after application of liquid or foam technologies, coupons were stored either vertically or horizontally for the range of decontamination times evaluated. The decontamination treatments were applied in a far greater than stoichiometric amount, since this would be consistent with the approach taken in decontaminating a large facility. Three coupons were extracted a few minutes after the initial application and then at 1, 8, and 24 h of decontamination contact time. Data points in the Results section represent the mean value of three replications of coupons tested in both horizontal and vertical orientation. Error bars represent 1 standard deviation of the mean.

2.6. Solvent extraction

Chemical agent was extracted from coupons using 10 mL of dichloromethane:acetone (1:1) and 15 min of sonication. Vinyl floor tile and latex-painted wallboard required a second extraction. Materials that deteriorated during extraction were filtered before analysis. No losses were observed in tests of CWA filtration in the solvent mixture using a 1- μ m syringe filter. Any liquid or foam that did not remain on the coupon was extracted using 10 mL of dichloromethane:acetone (1:1) and 15 min of sonication.

2.7. Analytical methods

Each 5- μ L sample of solvent extract was analyzed by GC–MS using a Hewlett Packard (HP) 6890 GC coupled to a HP5973 mass selective detector with the injection temperature set at 250 °C. Chromatographic separation was achieved using a DB-5MS column (30-m \times 0.25-mm i.d., 0.25- μ m film thickness), with the GC oven ramped from 40° to 250 °C over 35.5 min. The mass spectrometer was operated in full-scan mode (30–550 m/z) to identify possible CWA degradation products that could result from chemical interactions on a coupon surface.

3. Results

Data are reported as residual contamination (μ g or ng of CWA recovered) to link experimental outcomes to eventual health-risk-based cleanup standards for re-occupancy of civilian infrastructure. In addition, Table 1 reports the percentage of CWA removed over 24 h in the presence of decontamination reagent to provide a measure of the efficiency of each technique.

None of the captured liquid or foam that dripped off coupons had a detectable concentration of CWA. No toxic degradation products of HD (sulfones) and VX (EA2192) were observed in any solvent extracts of surfaces with or without decontamination.

Figs. 1 and 2 show decontamination performance against HD and VX, respectively, on horizontal nonporous or nonpermeable surfaces. GB decontamination was not evaluated on these surfaces because liquid droplets of GB applied to glass and stainless-steel surfaces resulted in persistence times of less than 1 h. Similarly, GD decontamination was not studied on stainless steel because of the short persistence of liquid droplets on that surface (below the detection limit of 1 μ g after 8 h of natural attenuation).

The HD contamination on both glass and stainless steel before application of any decontamination was measured to be \sim 700 μ g. Fig. 1(a) shows the result for HD on glass, where SDF, DF-200, and Decon Green all resulted in rapid and complete decontamination of HD to below detection levels (<100 ng residual contaminant). Decontamination using the bleach solution was slower, such that a measurable residual of 14- μ g HD remained 24 h after the bleach application. Fig. 1(b) shows the results for HD on stainless steel, where SDF and Decon Green resulted in rapid initial reactivity, similar to that on glass, whereas DF-200 reactivity appeared to be slower than that on glass and similar to the rate of the bleach solution. For stainless steel, both SDF and DF-200 reduced residual HD contamination to nondetectable levels 24 h after decontaminant application. Decon Green and bleach solution resulted in \sim 6 μ g of HD residual remaining on a coupon surface 24 h after application of the decontaminant.

The VX contamination on both glass and stainless steel before any decontamination application was measured to be \sim 750 μ g. Fig. 2(a) shows the result for VX on glass, where DF-200 and Decon Green both resulted in rapid and complete decontamination of VX to below detection levels (<2 μ g residual). Decontamination using SDF was also rapid; however, residual VX (12 μ g) remained

Table 1
CWA decontamination percent after 24 h of decontamination treatment on horizontal samples.

Chemical agent	Decontamination method	Stainless steel (%)	Glass (%)	Concrete (%)	Vinyl tile (%)	Wallboard (%)
VX	None	0	7	46	0	0
	Bleach	67	60	85	42	50
	SDF	99+	98	98	50	50
	DF-200	98	99+	85	20	75
	Decon Green	99	99+	55	93	90
HD	None	42	46	97	14	0
	Bleach	99	98	97	50	93
	SDF	99+	99+	95	79	88
	DF-200	99+	99+	90	43	68
	Decon Green	99	99+	85	81	99+
GB	None	– ^a	–	99+	0	55
	Bleach	–	–	99+	94	75
	SDF	–	–	99+	94	55
	DF-200	–	–	99+	99+	99+
	Decon Green	–	–	99+	99+	99+
GD	None	–	99+	99+	60	50
	Bleach	–	99+	99+	78	98
	SDF	–	99+	99+	85	83
	DF-200	–	99+	99+	92	95
	Decon Green	–	99+	99+	98	99

^a Dash indicates the decontamination technology for the specified agent was not studied on this surface.

24 h after decontaminant application. The bleach solution showed some initial reactivity, but a residual (~300 µg) remained 24 h after its application. Fig. 2(b) shows the result for VX on stainless steel, where SDF resulted in rapid and complete decontamination of

VX to below the detection level. Decon Green and DF-200 showed similar rapid initial reactivity in the first hour, but both resulted in detectable VX residuals (3 µg and 15 µg for Decon Green and DF-200, respectively) 24 h after decontamination application. As with

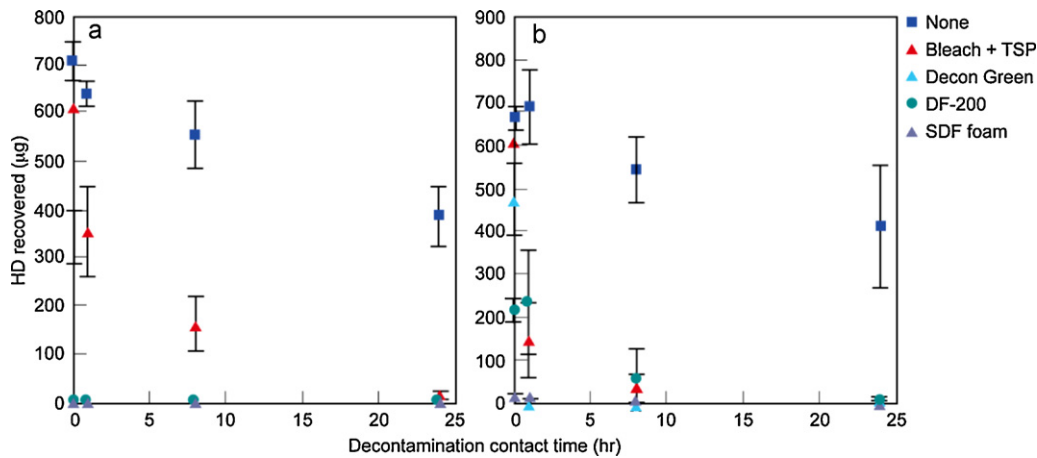


Fig. 1. HD decontamination on horizontal (a) glass and (b) stainless-steel surfaces.

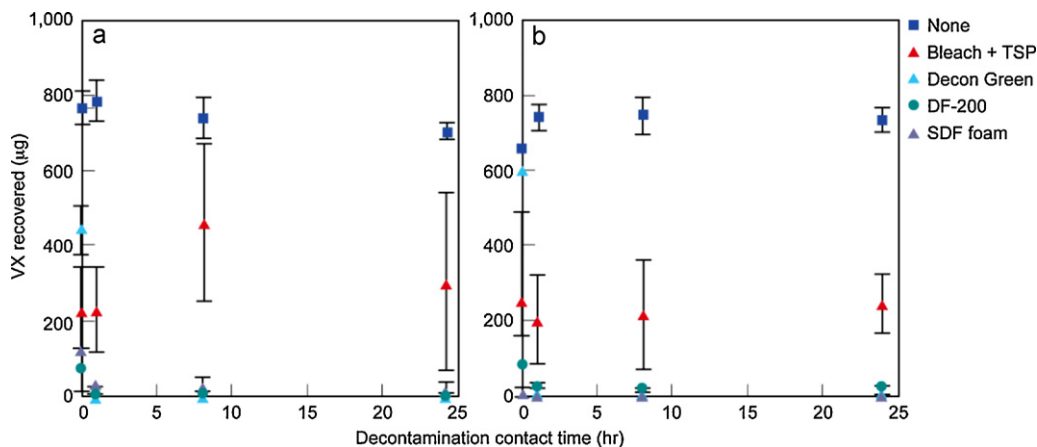


Fig. 2. VX decontamination on horizontal (a) glass and (b) stainless-steel surfaces.

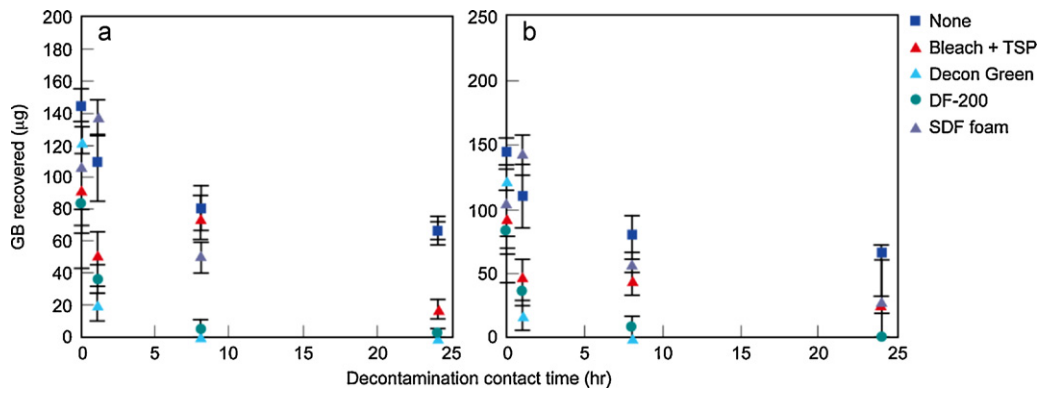


Fig. 3. GB decontamination on (a) horizontal and (b) vertical latex-painted wallboard.

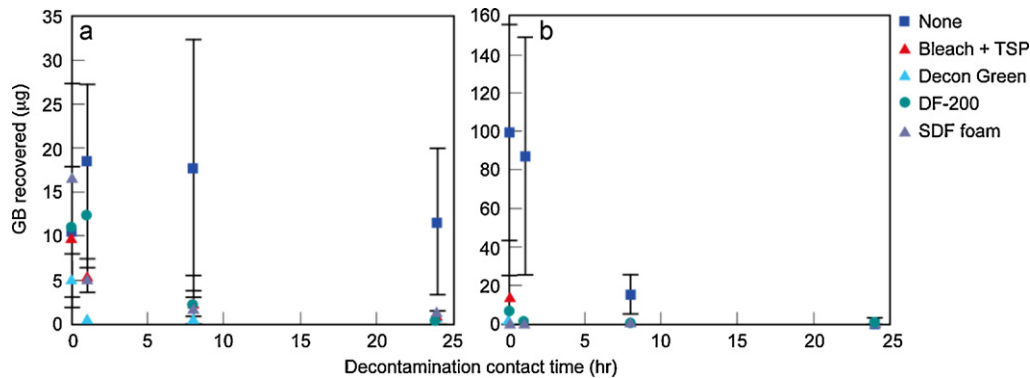


Fig. 4. GB decontamination on horizontal (a) floor tile and (b) concrete. Results for vertically oriented coupons (data not shown) were not statistically different from those for horizontally oriented coupons.

glass, bleach solution showed some initial reactivity, but a residual amount ($\sim 250 \mu\text{g}$) remained 24 h after its application.

Figs. 3–10 summarize the decontamination performance for GB, GD, HD, and VX on porous or permeable surfaces. In most cases, efficacy was apparent for each decontamination technology compared to no-treatment controls. Although the decontamination technologies typically demonstrated lower residual contamination levels than those on the no-treatment controls, in many cases some measurable residual contamination remained on a coupon surface even 24 h after decontaminant was applied.

Fig. 3(a) shows the results for horizontal latex-painted wallboard contaminated with GB, and Fig. 3(b) shows the results for vertical latex-painted wallboard. The GB contamination on wallboard before any decontamination was $\sim 150 \mu\text{g}$. Both Decon Green

and DF-200 reduced the GB residual contamination on latex-painted wallboard to near or below the detection limit ($<1 \mu\text{g}$), whereas SDF and the bleach solution resulted in residual contamination ranging from no difference compared to no-treatment controls (i.e., $80 \mu\text{g}$) to $20 \mu\text{g}$. The different foams, SDF and DF-200, give different results on wallboard reflecting their different (aqueous vs organic, respectively) chemical make up.

The performance of each treatment technology on GB-contaminated wallboard was similar for vertical and horizontal coupons, with most data points for each treatment overlapping one standard deviation of the mean for the 3 replications of the horizontal and vertical variations. The same was true of all remaining tests involving comparisons of coupons in vertical and horizontal orientations, regardless of the CWA tested or substrate evaluated.

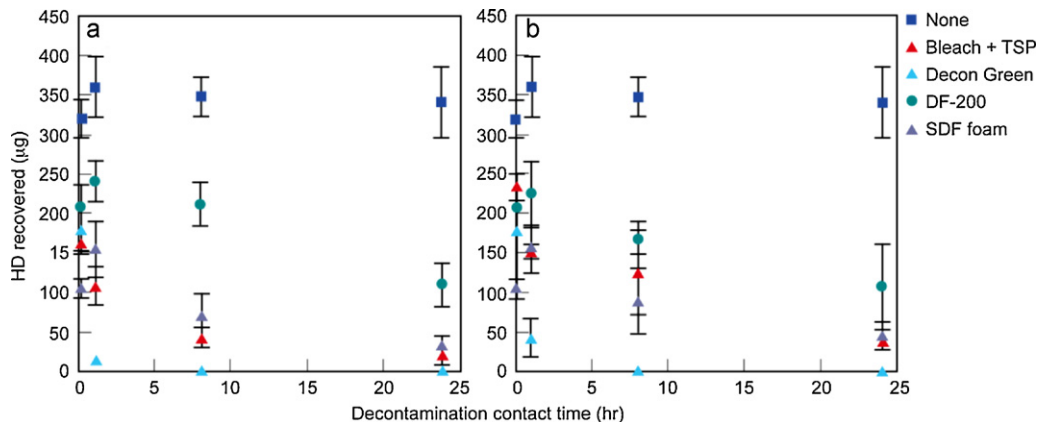


Fig. 5. HD decontamination on (a) horizontal and (b) vertical latex-painted wallboard.

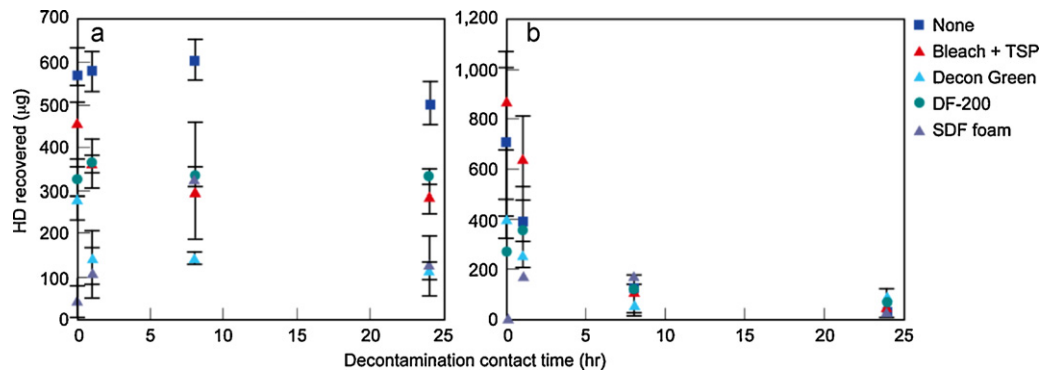


Fig. 6. HD decontamination on horizontal (a) floor tile and (b) concrete. Results for vertically oriented coupons (data not shown) were not statistically different from those for horizontally oriented coupons.

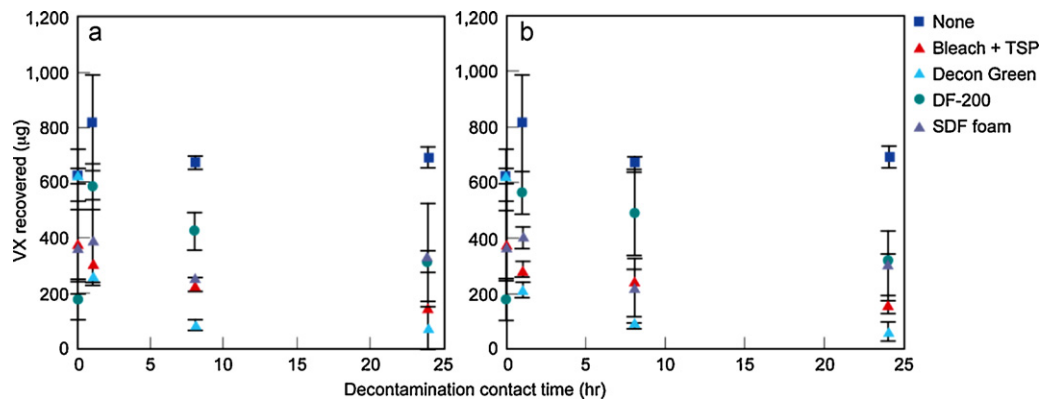


Fig. 7. VX decontamination on (a) horizontal and (b) vertical latex-painted wallboard.

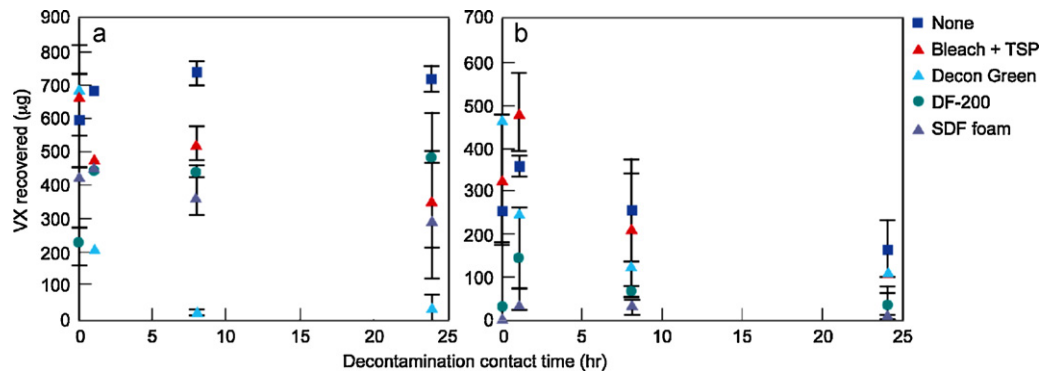


Fig. 8. VX decontamination on horizontal (a) floor tile and (b) concrete. Results for vertically oriented coupons (data not shown) were not statistically different from those for horizontally oriented coupons.

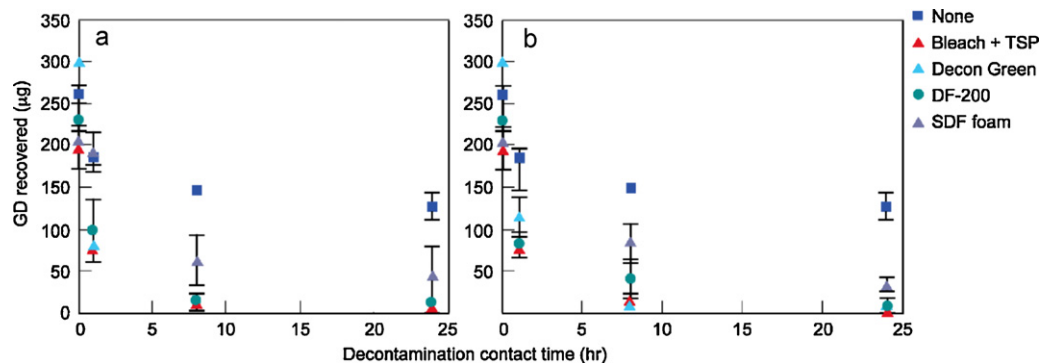


Fig. 9. GD decontamination on (a) horizontal and (b) vertical latex-painted wallboard.

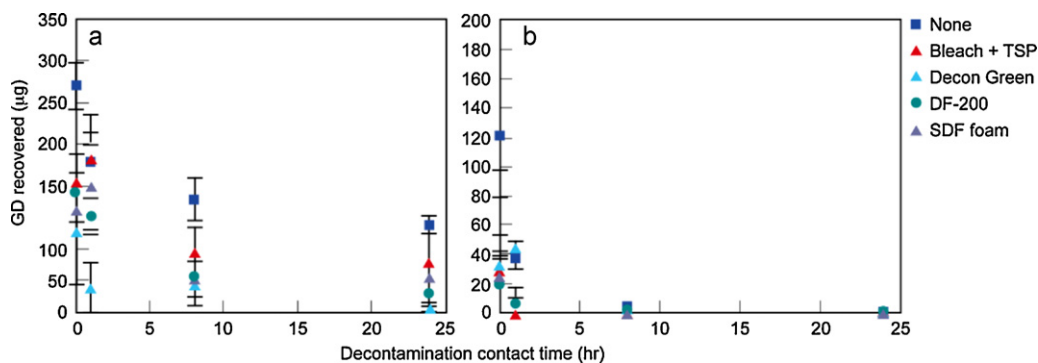


Fig. 10. GD decontamination on horizontal (a) floor tile and (b) concrete. Results for vertically oriented coupons (data not shown) were not statistically different from those for horizontally oriented coupons.

Because almost all the data points for each decontaminant technology overlapped one standard deviation of the mean for all replications of horizontal versus vertical positions, results for vertical orientation are not shown in some of the remaining figures.

Fig. 4(a) shows the results for horizontal vinyl floor tile contaminated with GB, and Fig. 4(b) shows results for horizontal concrete. The GB contamination on vinyl floor tile and concrete before application of any decontaminant was measured to be $\sim 18 \mu\text{g}$ and $100 \mu\text{g}$, respectively. Decon Green rapidly reduced the residual GB contamination in vinyl tile to near the detection limit ($<0.1 \mu\text{g}$), and DF-200 reduced GB residual contamination to near the detection limit within 24 h of application. Both SDF and the bleach solution resulted in residual contamination of $\sim 1 \mu\text{g}$ 24 h after decontamination application. Fig. 4(b) shows that although the no-treatment results indicate residual GB contamination levels are low ($\sim 1 \mu\text{g}$) on concrete after 24 h, each of the treatment technologies achieved $<1 \mu\text{g}$ between the initial application and 1 h of contact time. Each of the technologies tested resulted in nondetectable ($<0.1 \mu\text{g}$) residual contamination 8 h after application of decontaminant.

Fig. 5(a) shows the results for horizontal latex-painted wallboard contaminated with HD, and Fig. 5(b) shows results for vertical wallboard. The HD contamination on latex-painted wallboard before any decontamination application was measured to be $\sim 340 \mu\text{g}$. Decon Green was the only decontamination technology able to reduce residual HD contamination on latex-painted wallboard to below detection limits ($<1 \mu\text{g}$) within 24 h. SDF and bleach solution reduced the HD residual contamination to $40 \mu\text{g}$ and $25 \mu\text{g}$, respectively, whereas DF-200 resulted in $\sim 110 \mu\text{g}$ of residual contamination compared to no treatment ($\sim 340 \mu\text{g}$).

Fig. 6(a) shows the results for horizontal vinyl floor tile contaminated with HD, and Fig. 6(b) shows results for horizontal concrete. The HD contamination on vinyl floor tile and concrete before any decontamination application was measured to be $\sim 580 \mu\text{g}$ and $400 \mu\text{g}$, respectively. None of the treatment technologies tested was highly effective at decontaminating HD on vinyl tile. Decon Green and SDF resulted in residual HD contamination of $\sim 125 \mu\text{g}$ after 24 h of decontaminant application. DF-200 and bleach solution resulted in residual HD contamination of $\sim 300 \mu\text{g}$ after 24 h of decontaminant application.

Fig. 6(b) shows that residual CWA contamination on concrete decreased rapidly for each treatment technology evaluated. However, after 24 h of exposure to the decontamination mixtures, there was little difference between the treated and untreated control coupons, suggesting that the concrete tested has a reactivity that affects the observed degradation of HD more than the treatment technologies themselves.

Fig. 7(a) shows the results for horizontal latex-painted wallboard contaminated with VX, and Fig. 7(b) shows results for vertical wallboard. The VX contamination on latex-painted wallboard

before any decontamination was measured to be $\sim 700 \mu\text{g}$. Decon Green was the best decontamination technology of those studied for reducing residual VX contamination on latex-painted wallboard within 24 h. Nevertheless, its application resulted in measurable VX residual contamination ($\sim 70 \mu\text{g}$) after 24 h. Bleach solution demonstrated the next-best performance in this group of treatment technologies, but it resulted in VX residual contamination of $\sim 150 \mu\text{g}$ after 24 h. SDF and DF-200 left residual contamination of approximately $300 \mu\text{g}$ of VX on latex-painted wallboard.

Fig. 8(a) shows the results for horizontal vinyl floor tile contaminated with VX, and Fig. 8(b) shows results for horizontal concrete. The VX contamination on vinyl floor tile and concrete before any decontamination was measured to be $\sim 700 \mu\text{g}$ and $370 \mu\text{g}$, respectively. Decon Green was the best decontaminant of those evaluated for reducing residual VX contamination on vinyl tile within 24 h, but it resulted in VX residual contamination of $\sim 50 \mu\text{g}$ after 24 h. SDF, DF-200, and bleach solution resulted in greater residual VX contamination (ranging from ~ 250 to $500 \mu\text{g}$) 24 h after decontamination application. Fig. 8(b) shows that SDF best reduced the VX residual contamination level (to $6 \mu\text{g}$) on concrete. DF-200 and bleach solution reduced residual VX contamination to $\sim 40 \mu\text{g}$. Application of Decon Green resulted in $110 \mu\text{g}$ of VX residual contamination on treated samples of concrete evaluated after 24 h.

Fig. 9(a) shows the results for horizontal latex-painted wallboard contaminated with GD, and Fig. 7(b) shows results for vertical oriented wallboard. The GD contamination on latex-painted wallboard before any decontamination was measured to be $\sim 260 \mu\text{g}$. Decon Green and bleach were most effective at removing GD from latex-painted wallboard, leaving approximately $4 \mu\text{g}$ and $6 \mu\text{g}$ of residual, respectively, after 24 h. DF-200 resulted in $12 \mu\text{g}$ of residual, and SDF left $46 \mu\text{g}$, less than the no-treatment final amount of $125 \mu\text{g}$.

Fig. 10(a) shows the results for horizontal vinyl floor tile contaminated with GD, and Fig. 10(b) shows results for horizontal concrete. The GD contamination on vinyl floor tile and concrete before any decontamination was measured to be $\sim 270 \mu\text{g}$ and $120 \mu\text{g}$, respectively. All decontamination reagents and natural attenuation were effective at removing nearly all GD from concrete after 8 h, and the amount of residual agent was below the detection limit after 24 h. GD did persist on vinyl tile in the presence of decontamination reagents. Decon Green was the best decontaminant of those evaluated leaving $\sim 1 \mu\text{g}$ of GD after 24 h. DF200 was almost as effective, leaving $6 \mu\text{g}$. Bleach left $16 \mu\text{g}$ and SDF left $11 \mu\text{g}$ of GD, while 24 h of natural attenuation left $28 \mu\text{g}$.

4. Discussion

The results of our efficacy testing reinforce the difficulty associated with developing a universal decontamination technology

for cleanup of a CWA in a civilian setting. No perfect surface decontamination technology exists, largely because the various decontamination characteristics required to address all potential applications are likely incompatible. Except for bleach, all the decontaminants evaluated demonstrated excellent performance on nonporous and nonpermeable glass and stainless steel, which are surfaces that are the typical design basis of those decontamination technologies. Such surfaces do not pose transport challenges for decontamination because CWA remains a free liquid on the surface. Porous and permeable surfaces pose a more complex, coupled transport and reactivity challenge for decontamination.

The leading decontamination technology candidates we tested for CWAs often left substantial residual contamination on porous and permeable surfaces even after 24 h of contact time. Performance appeared to become progressively less effective as the persistence characteristics of the tested CWAs increased. Solvent-based Decon Green generally resulted in excellent performance on permeable polymers (latex-painted wallboard and vinyl floor tile) on which it could better penetrate hydrophobic surfaces compared with aqueous-based liquids and foams, whereas aqueous-based liquids and foams appeared to out-perform solvent-based Decon Green in penetrating pores of the polar surface of concrete.

Material compatibility also varies as a function of the type of formulation used in a given decontaminant. Aqueous-based products raise potential corrosion concerns, whereas solvent-based decontamination technologies are designed to avoid corrosion while penetrating into polymers and plastics. However, such penetration raises different materials-compatibility issues in that solvent-based systems have the potential to irreversibly alter polymer and plastic structures through swelling or weakening, eliminating their potential reuse following decontamination. In effect, the very characteristics that make a given decontamination technology most effective can also result in destructive processes that necessitate disposal of certain decontaminated materials.

5. Conclusions

The test results reported here, together with work being performed by the EPA, represent important steps toward improving our understanding of the efficacy of various decontamination strategies for the wide range of materials and surfaces relevant to the restoration of civilian infrastructure. Such understanding requires (1) identifying those materials that are easily decontaminated by the technologies available; (2) identifying those materials that should be removed because decontamination is impractical; (3) determining the most appropriate decontamination approach to apply in light of the contamination scenario and agent–material combinations; and (4) assessing all requirements related to waste disposal.

The potential interactions among a given CWA, substrate surface, and decontaminant are complex. Consideration of all potential interactions increases the likelihood that an efficient cleanup strategy will employ a range of decontamination technologies according to site- and incident-specific conditions. In situations where contaminated materials are destined for disposal, the decontamination criteria are much easier to satisfy and more options are available compared to situations in which materials are destined for reuse. Decontamination for reuse mandates not only that residual contamination be reduced to a value equal to or less than an established or recommended health guideline (clearance goal) but also that

the material being decontaminated not be damaged or destroyed, which can be highly problematic for the numerous surface types prevalent in typical civilian infrastructure. Where decontamination is impractical and disposal is unacceptable, at present only natural attenuation, or methods that enhance natural attenuation such as ventilation at elevated temperatures or relative humidity, remain as the most feasible options. Clearly, additional development is needed of decontamination technologies that will maximize material reuse in an effort to facilitate efficient facility restoration and minimize waste generation after a CWA release in a civilian setting.

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