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Summary of the Effectiveness of Volumetric Decontamination Methods as a Function of Operational Conditions

INTRODUCTION

One of the most efficient and thorough decontamination methods available for biological agents is fumigation. Fumigation has been used for over 100 years and is routinely applied to treat against termites and other pests, molds, and fungi. It is most useful in difficult-to-access spaces, such as heating, ventilation, and air conditioning (HVAC) systems, and where aerosolizable particulates are present, as might be the case with contamination from a *Bacillus anthracis* spore mixture manufactured as a powder. Fumigants include a wide variety of generally gaseous compounds with one general commonality: they are extremely toxic to living organisms, including humans. Therefore, fumigation must be conducted by highly trained and experienced workers.

The volumetric decontamination methods discussed consist of fumigation techniques that are used to decontaminate large areas contaminated by *B. anthracis* spores and any size area contaminated by aerosolized *B. anthracis* spores. These methods include fumigation techniques using methyl bromide, chlorine dioxide, formaldehyde, hydrogen peroxide, ethylene oxide, methyl iodide, ozone, and fogging with sporicidal liquids.

EPA has comprehensively evaluated numerous volumetric decontamination techniques for their efficacy against the spores of *B. anthracis* and its surrogates under a variety of operational parameters*.* However, in a wide-area incident, limited availability of supplies and trained personnel, logistical obstacles, or other unique challenges may force the use of alternative approaches to accomplish the mission at hand in an acceptable timeframe. Many of these alternative approaches might be unproven in the field and will have to be selected based on the best professional judgment of subject matter experts, such as building engineers and decontamination experts, or decision-makers.

VOLUMETRIC DECONTAMINATION METHODS AND OPERATIONAL PARAMETERS

Although numerous fumigants have been comprehensively evaluated, only one is currently registered as a sporicidal decontaminant [1] for inactivation of *B. anthracis* spores: DIKLOR G Chlorine Dioxide Sterilant Precursor (Sabre Oxidation Technologies, Inc.; EPA Registration No.

[1] To be considered effective and registered as a sporicidal decontaminant against *B. anthracis* spores, a decontaminant technology has to achieve a mean (average) 6 $\log_{10}$ reduction in the number of viable spores in relevant laboratory testing via approved protocols.

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73139-3; active ingredients: sodium chlorite {25%}; product label posted at: http://www.epa.gov/pesticides/chem_search/ppls/073139-00003-20140128.pdf). EPA issued a quarantine exemption for the use of several fumigation products against *B. anthracis* including: ethylene oxide, paraformaldehyde, and hydrogen peroxide vapor. The products listed in the quarantine exemption are supported by available safety and efficacy data, including data from EPA cited in this technical brief. In addition, Vaprox® Hydrogen Peroxide Sterilant (STERIS Corporation) is a registered sporicide that has been shown to be effective in previous *B. anthracis* decontamination events (EPA Registration No. 58779-4; active ingredients: hydrogen peroxide {35%}; product label posted at: http://www3.epa.gov/pesticides/chem_search/ppls/058779-00004-20120221.pdf).

Fumigation requires a great deal of preparation and monitoring to ensure that it is performed in a safe and efficacious manner. Precise control of operational parameters such as the concentration of the fumigant, relative humidity (RH), temperature, and duration of fumigation is required. EPA has identified many of the operational parameters necessary for specific volumetric decontamination techniques. Table 1 lists some, but not all, of the fumigant conditions that have been shown to be effective, or are the conditions that have been registered or used in previous *B. anthracis* decontamination events. Refer to the descriptions below the table for a more information or to the actual references.

Table 1. Fumigants and Operational Parameters

Fumigant Name [Reference Nos.]	**Description**	**Fumigation Operational Parameters**				**Comments**
		Concen-tration	**Relative Humidity %**	**Tem-perature °C (°F)**	**Duration (hours)**	
Methyl Bromide [1-4]	Colorless, odorless, toxic, non-flammable gas	212–300 mg/L	75	22–32 (72–90)	18-36	Recognized as a stratospheric ozone–depleting substance;* reacts with liquid aluminum
Chlorine Dioxide [5-18]	Yellowish-green gas; strong oxidizing agent; bleach/chlorine odor	200–3000 ppm	70–75	21–27 (70–80)	3-12+	Used during Capitol Hill *B. anthracis* response. Extensively tested by EPA.
Formaldehyde [19]	Colorless gas; pungent odor; flammable	1,100 ppm	50–90	16–32 (60–90)	10	Commercially available as liquid (formalin) and solid (paraformaldehyde)
Hydrogen Peroxide (vapor) [20-26]	Colorless liquid; little to no odor; strong oxidizer	5–400 ppm	Minimal	>18 (>65)	0.5 to 1 week, depending on concentration	Steris Product registration label specifies 30 minutes at 400 ppm, or 90 minutes at 250 ppm. However, tests (EPA and others) show these conditions are not always effective for some materials.

** "Exemption for Use" request/approval may be needed under Section 604 (d) of the Clean Air Act.*

Table 1. Fumigants and Operational Parameters *continued*

Fumigant Name	Description	Fumigation Operational Parameters				Comments
		Concen-tration	Relative Humidty %	Tem-perature °C (°F)	Duration (hours)	
Peracetic Acid (PAA) (fogging) [29-30]	Clear liquid; pungent vinegar-like odor; corrosive; oxidizer	> 10 mL of 4.5 % PAA per 1 m^3 volume	75–80	70–80	3 or more	PAA is produced and maintained in equilibrium with acetic acid, hydrogen peroxide, and water
Ethylene Oxide [27]	Flammable gas; reactive; potentially explosive; pleasant aroma	150–>600 mg/L	50–75	37–50 99–122)	1.5 to >3	Explosive nature precludes use for large volumes; suggested for fumigation of sensitive items inside chambers or smaller areas
Methyl Iodide [28]	Colorless non-flammable liquid; pungent odor	200 mg/L	>70	25 (77)	> 12	Although all pesticide registrations of methyl iodide products have been cancelled, the reagent is still widely available.
Ozone [31]	Colorless or blue gas with pungent odor	12,000 ppm	85%	21–27 (70–80)	9–12	

In general, fumigants are more effective with relatively higher gas concentrations, higher temperatures and relative humidity percentages, and longer durations/exposure times. However, these operational parameters are usually dependent to each other. Therefore, in some cases, the duration of the fumigation could be reduced if a higher gas concentration and higher temperature or percent relative humidity is used. Lower gas concentrations with a longer durations might also be effective. Additionally, concentration amounts might vary based on structure size and contents and the ability to maintain optimal relative and temperature.

The space to be fumigated must be relatively gas-tight or in some way able to control the exfiltration of the fumigant. Preventing leakage of the fumigant can be accomplished by several different control methods. One method would be to exert a slight negative pressure on the space, withdrawing fumigant and air from the space, and then filtering and scrubbing the withdrawn air as necessary before discharging it into the atmosphere. This method has provided improved air circulation in particular in lengthy and convoluted volumes, such as heating and ventilation ductwork, while also assuring that the correct fumigant concentration reaches all areas of the passage.

Operational parameters, temperature and RH, need be achieved and maintained at the optimal levels required for efficacious decontamination before and during the fumigation. Achieving and maintaining the necessary humidity levels in a space or building can be particularly difficult given the relatively high minimum values, often about 70%, required for most fumigants. The problem would be exacerbated in a northern city during winter. An industrial-level humidifier will likely be required when fumigating large spaces. Additionally, the initial sorptive capacity of the space due to furnishing and materials could be extremely high. The contents (e.g., paper, foam, fabrics, concrete, galvanized metal, water) within a volume to be fumigated should be factored into the fumigation decision process, as specific contents may act as sinks for fumigants, water vapor (humidity), and heat. To offset the sink effect, large amounts of paper may need to be removed or pre-humidified before fumigation and large amounts of foam may need to be removed.

The temperature requirements for fumigation vary according to the fumigant, with requirements starting at 16°C (60°F). The temperature will need to be assessed to determine if supplemental heating is required at any point before or during fumigation operations, and if heaters need to be distributed throughout the structure. Below are general guidelines for heating the structure:

- Multiple heaters may be used throughout the structure.
- Heaters should be controlled from outside the fumigation site to maintain the correct temperature. Many heaters will have thermostats on the units themselves to control the temperature.
- Power lines and lines for controlling the heaters need to be placed inside the fumigation structure.
- The HVAC system fans may be turned on to decontaminate the HVAC duct work as well as to help circulate air and fumigant within the structure. If additional heating is needed, the HVAC heating system may be used. If the heater is used, the heater exhaust must be open and routed back into the structure.

Achieving and maintaining gas concentration can also be challenging as gas concentrations can decline due to interactions with materials, be diluted by leakage, and decay naturally. Fumigation specialists will need to ensure that enough fumigant chemicals or their precursors are brought to the site so that the target concentration can be achieved and maintained in the volume for the target contact time, overcoming any losses due to adsorption, leakage, and/or decay. In addition to having enough mass of chemicals on site, the *rate* of injection of these chemicals into the building has to be high enough in order to overcome losses and increase concentration until the target is achieved. As an example, if the target concentration for chlorine dioxide (ClO_2) is 3000 ppm, the fumigation specialist must have an injection rate high enough to overcome losses, otherwise it may take days to reach the 3000 ppm target concentration or it may not be achievable at all.

Wind can complicate the fumigation of a large structure. Wind can induce pressure differentials, causing dramatic increases in exfiltration and infiltration of air in buildings. This condition can create problems from a health and safety standpoint (it could, for example, allow the fumigant to escape, exposing workers or the public), and increase the difficulty of maintaining optimum fumigant concentrations and the prescribed humidity and temperatures in the fumigated space. Therefore, it is advisable to consider the predicted weather prior to scheduling fumigation in larger structures and buildings.

Once fumigation is complete, aeration of the structure will be necessary to reduce fumigant concentrations to levels acceptable for reentry. Depending on the fumigant and the operational parameters used, aeration can be accomplished via natural aeration, operation of a scrubber (e.g., activated carbon system), or operation of negative air machines (NAMs) with high-efficiency particulate air (HEPA) filters. It is important to note that fumigant adsorption may be followed by latent desorption (off-gassing) for extended periods of time following the initial fumigation and this should be considered when planning and implementing the aeration process.

VOLUMETRIC DECONTAMINATION METHODS SITE PREPARATION AND FUMIGANT OPTIONS

General site preparation steps, a brief description of the various fumigant options, and an overview of sensitive material decontamination techniques are provided in this section.

Site Preparation Steps Common to All Methods

Many of the procedures for fumigation and fogging, including such actions as sealing of a room, tenting of a building, and set up of humidifiers, are identical or similar for each fumigant. The general preparation steps are summarized below, although not all of these steps may be required.

- Sealing, tenting, and elimination of air leakage.
- Installation of HEPA air scrubber.
- Installation of gas monitoring points.
- Installation of temperature and humidity monitoring instruments.
- Installation of fumigant generating equipment/gases and injection lines.
- Installation of temperature controls.
- Placement of fans.
- Placement of humidifiers.
- Elimination of flame sources (particularly for methyl bromide and formaldehyde).
- Final check and placarding.
- Ambient air monitoring planning and equipment.

Fumigant Options

Methyl Bromide (MB)

Methy bromide (also known as bromomethane) is a colorless, odorless, and nonflammable gas used as a pesticide to control insects, nematodes, weeds, pathogens, and rodents. In the United States, MB is used in agriculture as a soil fumigant, commodity treatment, and quarantine treatment. An “Exemption for Use” request/approval may be needed under Section 604 (d) of the Clean Air Act.[2]

[2] See EPA’s website on Critical Use Exemption Information, http://www.epa.gov/ozone/mbr/cueinfo.html

A laboratory study performed by EPA [1] showed that MB fumigation can effectively inactivate *B. anthracis* Ames spores; effective operational parameters are summarized in Table 2.

Table 2. Effective Operational Parameters for *B. anthracis* Decontamination with Methyl Bromide

Methyl Bromide Concentration (mg/L)	Relative Humidity (%)	Temperature °C (°F)	Duration (hours)
212	75	22 (72)	36
212	75	27 (81)	36
212	75	32 (90)	24
300	75	22 (72)	24
300	75	27 (81)	18

The following fumigation procedures are specific for MB.

- Site preparation (see *Site Preparation Steps Common to All Methods* above).
- Bring the operational parameters, temperature and RH, to the optimal levels required for efficacious decontamination.
- Fumigation.
  - Introduction of MB gas into the area being fumigated while maintaining operational parameters.
  - Monitoring of MB concentration in the fumigation area.
- Aeration.
  - Operation of scrubber (activated carbon system) until MB concentrations inside fumigation area are reduced to acceptable levels followed by natural aeration.

Test data and more specific operational details can be found in the EPA *Methyl Bromide Field Operation Guidance Report* [2] and other EPA studies [1, 3-4].

Chlorine Dioxide (ClO2)

ClO_2 is a non-flammable yellow-green gas at room temperature and a strong oxidizing agent with a bleach/chlorine odor. An effective biocide, it has been used for drinking water and wastewater disinfection and food plant sanitation. It has also been used in large-scale fumigations and to fumigate areas within the Hart Senate Office Building during the Capitol Hill *B. anthracis* incident. EPA test data also suggests that ClO_2 may be an effective decontaminant for soil [5] and surfaces covered with dirt or grime [6].

Previous tests and decontamination events using high levels of ClO_2 gas (e.g., 1000 – 3000 ppm) have demonstrated the inactivation of *B. anthracis* Ames spores, but the use of high ClO_2 levels also comes with drawbacks, such as issues with material compatibility and generation technology capacity. There are very few companies that have the technology to generate ClO_2 at a high enough rate to achieve 3000 ppm in an average sized building. Therefore, selecting gas concentrations that are lower and adjusting the operational parameters to reach the target fumigant conditions may be a more practical option for vendors with technologies that produce ClO_2.

EPA tested the efficacy of low level ClO_2 gas to guide its use and implementation for decontaminating indoor office material [7]. The study demonstrated the potential of using relatively low levels of ClO_2 gas (100-300 ppm), accompanied by longer exposure times, for effective decontamination of surfaces and spaces contaminated by *B. anthracis* Ames spores. The study noted that this decontamination approach may be better suited for areas that are not heavily contaminated and/or that do not contain significant quantities of porous materials such as carpet and wood. Some examples of effective operational parameters are shown in Table 3.

Table 3. Effective Operational Parameters for *B. anthracis* Decontamination with Chorine Dioxide

Chlorine Dioxide Concentration (ppm)	Relative Humidity (%)	Temperature °C (°F)	Duration (hours)
200-300	75	25 (77)	3-12+
3,000	>70	21–27 (70–80)	3
750	>70	21–27 (70–80)	12

ClO_2 fumigation procedures are listed below:

- Site preparation (see *Site Preparation Steps Common to All Methods* above).
- Bring the operational parameters, temperature and RH, to the optimal levels required for efficacious decontamination.
- Fumigation.
  - Introduction of ClO_2 gas into decontamination area while maintaining operational parameters.
  - Monitoring of ClO_2 concentration in decontamination area.
- Aeration.
  - Operation of scrubber (activated carbon system or dechlorinating scrubber solution emitter) until ClO_2 concentrations inside fumigation area are reduced to acceptable levels, followed by natural aeration.

Several additional EPA studies on ClO_2 fumigation [5-18] provide test data and details on operational procedures.

Formaldehyde

Formaldehyde is a colorless gas at room temperature with a pungent irritating odor. It is available commercially as a flammable colorless liquid in water solution as formalin or as a white crystalline solid, paraformaldehyde, produced by the polymerization of formaldehyde. Formaldehyde gas is generated from using either paraformaldehyde or formalin. Formaldehyde is used in building materials, to produce many household products, as an industrial fungicide, germicide, and disinfectant, and as a preservative in mortuaries and medical laboratories. Formaldehyde occurs naturally in the environment and is produced in small amounts by most living organisms as part of normal metabolic processes.

A laboratory study performed by EPA [19] showed that formaldehyde fumigation can effectively inactivate *B. anthracis* Ames spores on several surfaces including industrial carpet, bare pine wood, painted concrete, glass, decorative laminate, and galvanized metal ductwork. In the study, the formaldehyde concentration was maintained at approximately 1100 ppm with a relative humidity range of 50-90% and a temperature range of 16-32 °C (60-90 °F) during the 10-hr contact time.

Formaldehyde fumigation procedures are listed below:

- Site preparation (see *Site Preparation Steps Common to All Methods* above).
    - Setup of formaldehyde and quenching agent vaporizers.
- Bring the operational parameters, temperature and RH, to the optimal levels required for efficacious decontamination.
- Fumigation.
    - Introduction of formaldehyde gas into decontamination area while maintaining operational parameters.
    - Monitoring of formaldehyde concentration in decontamination area.
    - Introduction of quenching agent (typically ammonia) with a hot plate or other automated equipment to neutralize the formaldehyde.
    - Remove the powder formed from the neutralization process.
- Aeration.
    - Natural aeration.

Hydrogen Peroxide (H_2O_2)

Hydrogen peroxide, a colorless liquid with little to no odor, is a strong oxidizer used as a bleaching agent and disinfectant. While not flammable, it can cause spontaneous combustion of flammable materials and supports continued combustion because it liberates oxygen as it decomposes.

Vaprox Hydrogen Peroxide Sterilant is a registered H_2O_2 product (see previously cited registration information). The STERIS product registration label specifies fumigation conditions consisting of 30 minutes at 400 ppm, or 90 minutes at 250 ppm (both at a temperature of 18°C

(65 °F) or higher) when using the STERIS Vaporized Hydrogen Peroxide (VHP®) generator. However, tests (EPA and others) show these conditions are not always effective for some materials. EPA has tested VHP® generators and has identified a H_2O_2 concentration of 400 ppm with a minimal exposure duration of 6 hours (i.e., a cumulative exposure of 2400 ppm-hr at a temperature of 18°C (65 °F) or higher) to be effective for the inactivation of *B. anthracis* Ames spores. Several H_2O_2 vapor generators are commercially available, therefore, modifications to the operational parameters may be needed to conduct hydrogen peroxide fumigations using another vendor's generator. Additionally, lower concentrations with longer durations have also shown to be effective. Refer to the EPA studies on H_2O_2 fumigations [20-26] for test data and details on operational procedures.

The following are procedures for the use of H_2O_2 vapor for the fumigation of buildings and rooms:

- Site preparation (see *Site Preparation Steps Common to All Methods* above).
- Bring the operational parameters, temperature and RH, to the optimal levels required for efficacious decontamination.
- Fumigation.
    - Introduction of H_2O_2 gas into decontamination area while maintaining operational parameters.
    - Monitoring of H_2O_2 concentration in decontamination area.
- Aeration.
    - Operation of NAM(s) with HEPA filter until H_2O_2 concentrations inside fumigation area are reduced to acceptable levels.

Ethylene Oxide (EtO)

Ethylene oxide, an organic compound, is a carcinogenic, mutagenic, irritant, and anesthetic gas with a faintly sweet odor that is flammable at room temperature. EtO is widely used as a disinfectant and sterilant in hospitals and the medical equipment industry to replace steam in the sterilization of heat-sensitive tools and items. This gas is a candidate for decontaminating and sterilizing sensitive items and materials that might be found in museums, such as canvas paintings and fabrics, in the event of a biological agent release.

Because of the explosive nature of this gas, it should not be used on large volumes. Moreover, during EtO treatments, ethylene chlorohydrin formation is possible. Therefore aeration, a critical step post-treatment, may be required more than once, as items have been shown to off-gas EtO following fumigation. The most likely scenario would be fumigation of items with EtO in a large chamber or using the Andersen Products mobile system.[3] A limited number of smaller, field-deployable units are also possible for EtO fumigation.

EPA examined the efficacy of EtO against *B. anthracis* Ames and *B. atrophaeus* subsp. *globigii* spores applied to multiple materials, including the types of sensitive materials found in

[3] Andersen Products, http://www.anpro.com

museums or that could be sensitive to other types of decontaminants. Specifically studied were glass, bare pine wood, painted canvas, archival paper, silk, and carbon steel [27].

Decontamination efficacy was determined based on the $\log_{10}$ reduction in the number of viable spores recovered from the inoculated samples (with and without exposure to ethylene oxide).

EtO is an effective decontaminant against *B. anthracis* Ames under optimal combinations of concentration, contact time, temperature, and relative humidity. At a minimum, the combinations of parameters shown in Table 4 should be used for EtO to be effective against glass, bare pine wood, painted canvas, archival paper, silk fabric and carbon steel. In general, as the RH increases, so does the efficacy. Efficacious treatment is possible even with reduced amounts of EtO and a shorter contact time as the RH increases.

Table 4. Effective Operational Parameters for *B. anthracis* Decontamination with Ethylene Oxide

Etylene Oxide Concentration (mg/L)	Relative Humidity (%)	Temperature °C (°F)	Duration (minutes)
≥600	50	50 (122)	≥180
≥300	60	50 (122)	≥180
≥150	75	50 (122)	≥180
≥300	75	37 (99)	≥90

Methyl Iodide (MeI)

Methyl iodide, another fumigant that has been tested for the inactivation of *B. anthracis* Ames*,* can be used as an alternative to MB to expand the decontaminant capacity in the case of a wide-area *B. anthracis* incident. MeI has been used as a fungicide, herbicide, and soil disinfectant and has sporicidal properties similar to those of MB. Although all pesticide registrations of methyl iodide products in the US have been cancelled, the reagent is still available. Unlike MB, MeI is not an ozone-depleting substance and is thus not subject to the Montreal Protocol on Substances that Deplete the Ozone Layer.

EPA studied the decontamination of six types of common indoor and outdoor materials with MeI [28]. These materials were glass, ceiling tile, carpet, painted wallboard paper, bare pine wood and unpainted concrete. Decontamination efficacy tests were conducted with spores of virulent *B. anthracis* Ames and non-virulent strains (i.e., *B. atrophaeus* subsp*. globigii and B. anthracis* Sterne). Tests were conducted with various temperatures, RH levels, concentrations, and contact times to assess the effect of these fumigation operational parameters on decontamination efficacy. Findings showed that a 6-$\log_{10}$ reduction can be achieved at a temperature of 25 °C (77 °F), RH greater than 70%, and a MeI concentration of 200 mg/l held for a minimum of 12 hours. These results are similar to those achieved with MB. MeI has not been tested on a field-scale level, but site preparation and operational parameters would be similar to those for MB.

Peracetic Acid (PAA) **(fogging)**

Fogging is the process of aerosolizing a liquid into the air as microscopic droplets. It can be used for the volumetric decontamination of buildings, rooms, and sensitive items. It is important to select an appropriate fogging device. (Note: some inexpensive devices may not be as effective because they may produce relatively larger droplet sizes; larger droplets may tend to settle faster and not reach all surfaces in a contaminated space).

Theoretically, any sporicidal liquid could be fogged to decontaminate *B. anthracis* spores. Examples of other candidate liquid sporicidal chemicals include hydrogen peroxide, chlorine dioxide, formaldehyde, and pH-amended bleach. However, most of the commercially available foggers used for disinfection (such as for hospitals, clean rooms, veterinary facilities), and foggers reported in the scientific literature use peracetic acid or hydrogen peroxide.

The fogging procedures discussed here focus on the use of PAA, one of the most effective active ingredients in liquid sporicidal chemicals. However, the basic principles of fogging operation are applicable to most other sporicidal liquids.

PAA, a clear liquid with a pungent, vinegar-like odor, is corrosive and an oxidizer. The effective operational parameters fogging with PAA include a concentration of > 10 mL of 4.5% PAA per 1 m^3 volume with a duration of 3 or more hours at 75-80% RH and 21-27 °C (70-80 °F).

The following are procedures for fogging, with emphasis on the use of PAA:

- Site preparation (see *Site Preparation Steps Common to All Methods* above).
  - Installation of fogging equipment and related supplies including the air supply for the fogger.
- Fogging.
  - Introduction of fogged sporicidal liquid into decontamination area while maintaining operational parameters.
  - Monitoring of sporicidal liquid concentration in decontamination area.
- Aeration.
  - Natural aeration.

Refer to the EPA studies on fogging with PAA [29-30] for test data and additional details on operational procedures.

Ozone

In an EPA study [31], ozone fumigation was evaluated for its ability to decontaminate building materials inoculated with *B. anthracis* and *Bacillus subtilis* spores. The study concluded that ozone gas is a promising fumigant decontamination technology for the inactivation of *B. anthracis* Ames spores on building materials, provided that sufficient concentration, contact time, temperature and RH are achieved for the various materials being decontaminated. In general, decontamination efficacy improved with increasing ozone concentration and RH, and was affected by the material. The effective operational parameters were identified as a concentration of 12,000 ppm with an exposure duration of 9-12 hours at 85% RH and 21-27 °C (70-80 °F).

SENSITIVE MATERIAL DECONTAMINATION TECHNIQUES

The compatibility of sensitive materials and decontamination agents should be understood when deciding on a cleanup approach. Table 5 lists findings of EPA studies [7, 32] on fumigants and material compatibility. Tests may be needed for items not evaluated in the past:

Table 5. Findings from EPA Fumigation Tests of Electronic Equipment (Desktop Computers, Monitors, Fax Machines, Cell Phones, CDs) with Chlorine Dioxide, Hydrogen Peroxide, Methyl Bromide (with 2% Chloropicrin), and Ethylene Oxide *

Fumigant Tested [32]	**Findings**	**Comments**
Chlorine Dioxide	At 3000 ppm, fumigation caused some corrosion around the edges of desktop computers, left powdery residue and damaged some CD/DVD drives; with the exception of some DVD drives, the computers were still in operation with no replacement parts one year after fumigation; a separate study [7] showed less detrimental impact on computer functionality when fumigating with lower levels of chlorine dioxide.	Computers fumigated with chlorine dioxide were more prone to physical/functional deterioration than those fumigated with hydrogen peroxide.
Hydrogen Peroxide	Fumigation did not appear to affect the electronic components tested; computer performance did not appear to be significantly affected up to one year following fumigation.	Fumigation can be considered a valid option for whole-building/room decontamination with sensitive items, but process humidity and exposure time must be very carefully planned and controlled to minimize damage to sensitive items.
Methyl Bromide (with 2% Chloropicrin)	Recommended for porous sensitive items (books, documents, photographs, etc.). It appears to be the most compatible and least damaging to most sensitive items. Power supplies in all MB-fumigated computers failed, some catastrophically, due to the chloropicrin; some corrosion of low carbon steel and steel outlet/switch boxes seen; other materials with potential for damage include metal bearings and CD/DVD drives.	For whole building/room fumigations, methyl bromide is recommended for porous sensitive items and is recommended over hydrogen peroxide for most sensitive items. Do not use methyl bromide with added chloropicrin for sensitive items: **chloropicrin has been shown to cause oxidation or adverse effects on the electronics.**
Ethylene Oxide	Little or no impact for materials tested; generally the most material-compatible method for decontamination of high-value irreplaceable objects; treatment is complicated and must be performed precisely.	Use in an extremely well-ventilated area; not suitable for wide-area fumigation in a building or an environment with an ignition source; it is recommended that the **work either should be conducted in a dedicated off-site facility** or objects removed to a controlled environment in another spot within the site.

* It is important to note that the results are for the specific conditions to which the material or equipment was exposed during testing. Less impact is expected when fumigating at lower concentration or RH.

CONCLUSION

Many volumetric decontamination technologies exist. These methods include fumigation techniques using methyl bromide, chlorine dioxide, formaldehyde, hydrogen peroxide, ethylene oxide, methyl iodide, ozone, and fogging with various agents. Some of the decontamination technologies presented in this document have proven successful during real-world responses. In contrast, other technologies have been demonstrated to be effective during laboratory testing and have not been fully evaluated at the field-scale level. During a response, users of this document might need to extrapolate experimental findings from the laboratory to the field, then field-prove and modify the decontamination techniques as necessary to help establish the process-knowledge required for the environmental- and site-specific conditions.

DISCLAIMER

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