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Impact of sporicidal fumigation with methyl bromide or methyl iodide on electronic equipment

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Abstract

The effect of sporicidal fumigation with methyl bromide or methyl iodide on the functionality of valuable electronic equipment was evaluated using desktop computers as surrogates under target conditions of 200–250 mg/L fumigant for 48 h at 24–30 °C and 75–85% RH. Methyl iodide fumigation damaged light-emitting diodes and optical films in computer displays that were powered-on during fumigation. After five months of post-fumigation operation, five out of six methyl-bromide-fumigated and all six methyl-iodide-fumigated DVD ± RW optical drives failed. Deterioration of rubber spacers critical to maintaining correct disc geometry caused the failure. Metal coupons, included to measure corrosion, showed no significant differences in weight gain between control and fumigation conditions. Relative humidity sensors exhibited a substantial and some-times irreversible reduction in sensitivity during and after methyl iodide fumigation. Methyl bromide and methyl iodide can cause damage to electronic equipment, but damage seems to be limited to organic materials rather than corrosion of metal surfaces.

Keywords

Fumigation; Methyl bromide; Methyl iodide; Anthracis; Decontamination; Material compatibility

1. Introduction

Damage to high-value electronic equipment such as sensitive medical, communication, or infrastructure-control systems would be a major concern during the remediation of buildings

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Declaration of interest

Rudolf H. Scheffrahn is an inventor and original assignee of the patent "Method of decontamination of whole structures and articles contaminated by pathogenic spores".

contaminated with a biothreat agent such as *Bacillus anthracis* (the causative agent of Anthrax). During the 2001 Amerithrax incident, seven mail or office buildings contaminated with *Bacillus anthracis* were fumigated with either chlorine dioxide or hydrogen peroxide, or underwent formaldehyde fumigation of subsections containing mail sorting machines (Schmitt and Zacchia, 2012). Small items of value, computer disks reportedly among them, were fumigated in chambers off-site with ethylene oxide (Canter et al., 2005). Although these buildings undoubtedly contained electronic equipment of value, the total value is likely far less than that of the sensitive equipment found in an airport, hospital, or data center.

Fumigants available for volumetric decontamination of buildings fall into two categories: oxidants (e.g., hydrogen peroxide, chlorine dioxide), and alkylating agents (e.g., formaldehyde, methyl bromide (MB), methyl iodide (MI)). The United States Environmental Protection Agency (USEPA) conducted material compatibility testing of hydrogen peroxide, chlorine dioxide, MB, and ethylene oxide under sporidical conditions using desktop computers as surrogates for valuable electronic equipment (U.S. Environmental Protection Agency, 2010a; b, 2012). Although hydrogen peroxide caused no damage to electronic equipment, separate studies using three different model computers reported damaging corrosive effects of chlorine dioxide (3000 ppm for 3 h) on electronic equipment (U.S. Environmental Protection Agency, 2010a; b, 2012). Additionally, fogging with a liquid solution of hydrogen peroxide and peracetic acid was effective under some conditions against *Bacillus anthracis* on subway railcar materials and did not cause visual damage to a variety of materials (Richter et al., 2018), but the effect of fogging on electronic equipment was not investigated. Less aggressive chlorine dioxide fumigation conditions (lower concentrations with longer contact times) were effective in laboratory testing for specific conditions and were used to decontaminate electronics in the lab and field without substantial impact (Czarneski, 2009; Girouard and Czarneski, 2016; Lorchheim and Lorchheim, 2013; U.S. Environmental Protection Agency, 2014b).

Although the USEPA reported that ethylene oxide did not damage computers, the explosive concentrations required to reach sporidical activity and its reported carcinogenicity limits it to treatment of deenergized electronics moved to chambers (Lynch et al., 1984; U.S. Environmental Protection Agency, 2014a). Similarly, in-chamber treatment with high-pressure carbon dioxide and water can effectively decontaminate sensitive equipment (Calvo and Casas, 2018), but cannot be employed on a whole-building scale. A recent US Navy study used hot humid air to decontaminate an aircraft inside a hangar, but the impact on aircraft functionality was not reported (Buhr et al., 2016). Mail sorting machines fumigated with formaldehyde during the Amerithrax incident were successfully returned to service and formaldehyde fumigation is routinely used to decontaminate laboratories (Canter et al., 2005; Science Applications International Corp, 2005), but its classification as a possible carcinogen limits its use (Spotts-Whitney et al., 2003).

Identification of commercially-available technologies for decontaminating facilities containing high-value electronic equipment is needed to address known and potential capability-gaps and limited capacity, which could be exceeded in the event of a wide-area incident. Porous materials are difficult to decontaminate using hydrogen peroxide and field-scale structural fumigations have reported difficulties maintaining target concentrations

(Rogers et al., 2005; Science Applications International Corp, 2005; U.S. Environmental Protection Agency, 2011, 2013; Wood et al., 2016a). Furthermore, additional studies could reveal incompatibilities of hydrogen peroxide or low concentration chlorine dioxide with critical materials not yet tested. MB is a FIFRA-registered pesticide (Meth-O-Gas 100: EPA no. 5785–11) labeled for use against many insects, but not as a sporicide against *B. anthracis* (U.S. Environmental Protection Agency, 2017a). Although subject to commercial restrictions as an ozone-depleter, MB is used under critical use and quarantine exemptions (Federal Register, 2015). Unlike chlorine dioxide, MB is not an oxidizing agent and there is no evidence of its gas-phase corrosiveness to metals found in electronics. Separate field trials fumigating a mock-home and a subway railcar containing computers and other electronic equipment reported no damage at the end of the trials (Serre, Personal communication; Serre et al., 2015; U.S. Environmental Protection Agency, 2017b).

A previous USEPA study, however, evaluating the impact of fumigation using a mixture of 98% MB and 2% chloropicrin (added as a warning agent) on electronic equipment (300 mg/L at 75% relative humidity and 37 °C) reported substantial damage to exposed computers. Analysis of the corroded surfaces by LGS innovations, LLC (Alcatel-Lucent, Murray Hill, NJ), implicated chloropicrin in most of the observed damage (U.S. Environmental Protection Agency, 2012).

The present study evaluates the impact of fumigation using MB without chloropicrin under target conditions that were sporicidal in the lab and recently tested in the field (Serre et al., 2015; Wood et al., 2016b). Although no longer a FIFRA-registered pesticide and not currently in use in the US (Sutton et al., 2015), the effect of MI under conditions reported to be sporicidal in the lab was also evaluated (U.S. Environmental Protection Agency, 2014c). MI is expected to be less available than MB during the remediation of biothreat-impacted buildings, but could see niche use if compatible with electronic equipment. In the present study, desktop computers were used as surrogates for high-value equipment and the impact of sporicidal fumigation on computer functionality was assessed using visual inspection and diagnostic software. Metal coupons used in the electronics industry were included to test for corrosion.

2. Experimental

2.1. Equipment, chemicals, and spores

Desktop computers (Precision Tower 3620) and displays (E1916H) were obtained from Dell Inc. (Round Rock, Texas; specifications found in Table S1 in Supplementary material). Biological indicators (nominally 1×10^6 CFU *Bacillus anthracis* Sterne spores on 9-mm stainless steel disks in Tyvek envelopes) were obtained from Yakibou, Inc. (Apex, NC). Tryptic soy broth and tryptic soy agar were obtained from Becton, Dickinson and Company (Sparks, MD). MB (Meth-O-Gas 100) was obtained from Great Lakes Chemical Corporation (West Lafayette, IN) and MI (> 99.9%) was obtained from Qingdao Tocean Iodine Chemical Company (Qingdao, China). Aluminum (99.99%), copper (99.999%), Tin (99.998%), and silver (99.998%), were obtained from Alfa Aesar (Tewksbury, MA).

2.2. Computer functionality evaluation

Computer functionality was assessed through visual inspection and PC Doctor (PC-Dr) Service Center version 10.0.6689.55 (PC-Doctor, Inc., Reno, NV), a commercial software for computer diagnostics that tests all major computer subsystems. Names of these tests, number of trials run during each evaluation, and corresponding subsystems tested are in Table S2 in Supplementary material. Unless otherwise stated, tests were run using the default settings provided by the manufacturer. During evaluation, computers were operated on grounded electrostatic discharge stations; the operator was also grounded.

Computers underwent a baseline evaluation before shipment to the fumigation site and were evaluated again immediately before fumigation. Four weeks after fumigation, the computers were reenergized and evaluated weekly for 6 weeks and then once every 4–5 weeks for an additional 33 weeks. During shipment and storage, computers were kept in corrosion and static resistant bags (Static Intercept, Engineered Materials, Inc., Buffalo Grove, IL).

After the first post-fumigation evaluation, computers were kept active using BurnInTest V8.1 Pro 1018 (BIT) (PassMark Software Pty Ltd, Surry Hills, Australia), which ran a script that followed a daily cycle of 50% load for 8 h (logging any errors that cause the cycle to fail), 16 h of sleep, and a reboot. On the fifth day of the cycle, instead of rebooting, the computer was programmed to sleep for 40 h. This cycle simulates the varied activity level of electronics in the field and elicits hardware failures that require a period of use before manifesting.

2.3. Coupon preparation and weighing

Coupons (5 replicates of each metal per test condition) were 2-cm by 5-cm and cleaned with acids and/or solvents as described in Supplementary material. Before and after fumigation, coupons were photographed and weighed three times using a Sartorius M5P-000V001 microbalance after a 24-h equilibration at 22.2 ± 0.3 °C and $35 \pm 1\%$ RH. Coupons were mounted on a fixture using nylon standoffs and screws (Fig. S1 in Supplementary material) and stored in corrosion resistant bags until fumigation. Reference coupons remained in the corrosion resistant bag at ambient laboratory conditions. The initial mass and manufacturer-reported metal density and thickness were used to calculate the exposed surface area of each coupon. The change in mass for each coupon was normalized by its exposed surface area.

2.4. Fumigation efficacy

Before fumigation, five biological indicator (BI) strips were affixed to the inside of the removable side panels of the computers (Fig. S2 in Supplementary material) and the outside of one powered-off computer. Immediately after fumigation, BI strips were removed from the computers and stored in individual air tight bags (Zip Lock, Star Poly Bag, Inc., Brooklyn, NY) at 4 °C until analysis for “growth” or “no growth,” as described in Serre et al. (2015). Five positive and five negative controls were run in conjunction with test samples. Additionally, all samples were plated on tryptic soy agar and incubated overnight at 35 °C to confirm the visual results and to confirm by comparing test samples to positive control samples that no organisms had contaminated the samples.

2.5. Humidity measurements and effect on humidity sensors

Temperature (T) and relative humidity (RH) sensors were included in the fumigations to monitor environmental conditions and to evaluate the effect of fumigation on functionality. The effect on sensor functionality was assessed before fumigation and six weeks after fumigation by measuring RH in a 75% RH cell prepared using an aqueous solution of sodium chloride as described in ASTM E104–85 (ASTM International, 1996). During fumigation, one HOBO U-10 T/RH logger (Onset Computer Corp., Cape Cod, MA) was affixed to the inside center floor of each computer (Fig. S3 in Supplementary material) to capture the difference in internal T/RH between powered-on and powered-off computers. HOBO ZW-003 T/RH monitors were also included during fumigation to monitor real-time conditions as described in section 2.6.

2.6. Fumigation

The fumigation chamber was a rectangular 1-m³ stainless steel chamber with a removable lid, bolted closed through a closed-cell foam-rubber gasket (No. 8694K78, McMaster-Carr, Douglasville, GA), and had two polycarbonate windows. Each window was penetrated with a stainless-steel fitting that held a rubber septum through which liquid was injected. Six computers (including display, keyboard, and mouse) and a set of metal coupons were placed inside the fumigation chamber (Figs. S4 and S5 in Supplementary material). Three computers were powered-on and cycled between 10 min of 100% load and 20 min of sleep using the BIT software while the other three remained powered-off. Computer optical drives were empty and inactive during fumigation. Five fans with manufacturer reported air flows of 5000 L/min were placed inside the chamber to improve mixing. Computers and coupons were fumigated at 26–30 °C and 75–85% RH for 48 h with either MB or MI under a target concentration of 200–250 mg/L fumigant, or held in a fumigant-free control at the same temperature and humidity.

A non-dispersive infrared detector (ND-IR) (MB-ContainIR, Spectros instruments, Hopedale, MA) recorded the concentrations of MB or MI every 20 min. MB was quantified using the preprogrammed manufacturer-certified calibration curve (certified $\pm 4\%$ over full range 1 month before use). An MI calibration curve was constructed by injecting known volumes of MI into a separate 240-L stainless steel chamber and allowing the liquid to evaporate to produce concentrations of 193, 289, and 385 mg/L until a stable reading was obtained from the ND-IR detector.

Two HOBO ZW-003 wireless sensors placed inside the fumigation chamber measured real-time temperature and RH. Temperature was maintained by placing the chamber in temperature-controlled room. RH was maintained by periodically injecting water into the chamber through the rubber septum injection port.

MB was added as a liquid by inverting a cylinder of MB and allowing the liquid to flow through a polyvinylidene difluoride (PVDF) tube bored through the rubber septa and into an evaporation pan inside the chamber. The mass of MB was measured as weight loss of the cylinder during transfer. MI was injected through the rubber septa as a chilled liquid using a gastight syringe. During injection of fumigants, a vent in the chamber connected to the

outdoors was opened to maintain atmospheric pressure until it looked as though most of the fumigant had evaporated and the concentration was no longer increasing. The final fumigant concentration in the chamber was confirmed by ND-IR. The target concentrations were achieved within 40 min of the first injections and several injections were made throughout the exposure phase to maintain the target concentrations. A port connected to a 60-L PVDF pressure relief bag remained open to allow for gas to expand and contract with fluctuating temperature. After 48 h, the chamber was aerated by pumping fumigant-laden air out of the chamber to the outdoors for 4–5 h after which the chamber was opened by professional fumigators.

3. Results and discussion

3.1. Fumigation conditions achieved

The average and range of measured fumigant concentration over the 48-h exposure phase was 236 mg/L (196–285 mg/L) for MB and 220 mg/L (204–254 mg/L) for MI. Temperature and RH achieved are presented in Table 1. Time course data for the duration of each experiment are shown in Fig. S6 in Supplementary material. Due to an unexpected downward bias of RH measurements during the fumigation with MI, accurate RH measurements are not available (see section 3.2). The downward bias resulted in unnecessary addition of water to the chamber, which was halted after condensation was observed on the inside windows of the chamber.

3.2. Environmental conditions and fumigant effect on sensors

The effects of fumigation on the performance of RH sensors placed in the bulk chamber (HOBO ZW-003) and inside computers (HOBO U-10) were evaluated. Both the ZW-003 and U-10 sensors behaved as expected during and after MB fumigation. The ZW-003 sensors exhibited a downward bias during fumigation with MI, which was discovered when adding additional amounts of water to correct an unexpected drop in humidity did not result in reaching the target RH value (Fig. S7), but condensation was observed on the inside windows of the chamber. The downward bias was reversible; six weeks after fumigation, readings of the two MI-fumigated ZW-003 sensors placed in a 75% RH calibration chamber were similar to those recorded before fumigation (72.1–72.7 before and 79.7–77.0 %RH after).

U-10 sensors (placed inside computers) showed a more substantial downward bias, but unlike the ZW-003 sensors, did not regain sensitivity when evaluated 6 weeks after fumigation (Fig. 1). The U-10 sensors included in the fumigant-free control chamber showed a moderate reduction in sensitivity that could be due to a low concentration of residual MI left in the chamber; the control condition was completed after the MI fumigation. Although the chamber was opened and aerated to less than 1 ppm between trials, once the chamber was resealed the concentration may have increased as MI diffused out of items left in the chamber that were previously exposed (power strips, fans, etc.). In work to be published elsewhere, release of volatile organic compounds from computers was measured after each exposure; computers in the control condition released detectable amounts of compound, suggesting exposure to MI, but unexposed reference computers did not. Evaluation of the

U-10 loggers by the manufacturer confirmed that the T/RH sensor subcomponent was the cause of the failure and the manufacturer reported a yellow discoloration (Fig. S8 in Supplementary material) of the sensors from the control and MI-fumigated conditions (Murphy, Personal communication-b).

It is not known why the U-10 loggers sustained permanent damage, while the ZW-003 sensors recovered. The two units use the same model sensor (Sensirion SHT15), but the ZW-003 sensor is behind a membrane (possibly shielding it from some of the fumigant) (Murphy, Personal communication-a). During a field-scale fumigation, RH sensors with greater resistance to chemical interference would be needed for use with MI.

3.3. Fumigation efficacy

To assess the sporicidal effectiveness of MB and MI fumigation, BI strips were evaluated for growth/no growth after fumigation. Six out of thirty-five MB-fumigated BI strips and five out of thirty-five MI-fumigated BI strips had positive growth. See Table S3 in Supplementary material for BI growth status by position. All 35 BIs included in the fumigant-free control run were positive for growth. There was no statistically significant difference between the number of BIs with positive growth inside powered-on and powered-off computers for either fumigant (Fisher's exact test, $\alpha = 0.05$, Sigmaplot 13.0). Under the tested fumigation conditions, the difference in RH (Table 1) between powered-on and powered-off computers and between the computers and the bulk chamber did not substantially affect fumigant efficacy. During the fumigation of powered-on equipment in the field, however, differences in relative humidity between the inside of equipment and the bulk facility will depend on the type of equipment being fumigated.

3.4. Corrosion of metal coupons

Metal coupons were used to observe visual changes to the surface of the metal and to measure corrosion-induced weight gain. Only copper coupons showed a noticeable difference in appearance compared to the reference coupons after fumigation. Fumigated copper coupons had several small areas (approximately 1% of the surface area) of green and brown discoloration (3 out of 5 coupons for MB and 2 out of 5 coupons for MI). Control coupons had very small spots of discoloration not visible in photographs. See Figs. S9–S13 for photos of discolored coupons compared to reference coupons. An unexpected reaction that occurred while cleaning copper coupons as described in Supplementary material, however, makes it difficult to determine whether the discoloration observed after fumigation was an enhancement of damage caused during the initial cleaning process (Fig. S14). All increases in coupon mass were less than $1 \mu\text{g}/\text{cm}^2$; no significant differences were detected between coupons fumigated with MB or MI and those in the control condition using a one-way ANOVA followed by Dunnett's test for multiple comparisons ($\alpha = 0.05$) in Sigmaplot 13.0 (Fig. S15). In a previous USEPA study, fumigation with chlorine dioxide or methyl bromide with chloropicrin did not cause noticeable differences in the physical appearance of coupons of select aluminum or copper alloys (U.S. Environmental Protection Agency, 2012).

3.5. Effect on computer functionality

Desktop computers were fumigated under sporadic conditions with either MB or MI or exposed to a fumigant-free control environment at similar T/RH. The most substantial effect on computer functionality was damage to the computer displays that were fumigated with MI, particularly the computer displays that were powered on. All three powered-on monitors had reduced brightness and a bluish tint compared to controls (Fig. S16a in Supplementary material), while powered-off monitors had slightly reduced brightness (Fig. S16b). One powered-on monitor was disassembled and compared to an unexposed reference monitor. Damage was traced to the strip of light-emitting-diode backlights, which emitted blue light or no light instead of the white light emitted by those of the unexposed monitor (Fig. S17 in Supplementary material). The light-diffusing and polarizing films, which sit behind the liquid crystal screen, were yellow compared to those of unexposed monitors. Visual inspection of the exterior and interior surfaces of computers showed no other substantial effects. The cause of this damage is unknown, but could be due to either the MI, the condensation observed during the test (see section 3.2), or a combination of the two.

After 22 days of post-fumigation operation, the power supply unit (PSU) of one MB-fumigated computer that was powered-off during the fumigation failed. No visual differences were observed between the inside components of the failed PSU and that of a reference computer (unexposed). In addition to having a blown fuse, probing with a multimeter (set to measure continuity) revealed that one of three metal-oxide-semiconductor field-effect transistors (MOSFET) was internally shorted. No visual damage to the MOSFET or corrosion was observed. The PSU was replaced with one from a reference computer that had not been fumigated and the computer continued to operate without failure for the remainder of testing. In the previous USEPA study fumigating with MB and chloropicrin, all six fumigated computer PSUs eventually failed (U.S. Environmental Protection Agency, 2012). In that study, analysis of one failed PSU attributed the damage to the chloropicrin rather than to MB.

A vendor of high performance computing hardware reported a 1-year field-failure rate of 1–2% for PSUs, stating that the majority of failures were voltage issues including shutting off under load or not powering on (Bach, Personal communication). Using a binomial probability distribution, if the expected failure rate is 2%, then there is an 11.4% probability of having one or more PSUs in the random selection of six computers used in the present study (Pagano et al., 2000). There was no significant difference in the number of failed power supplies between the control group and MB fumigated group ($n = 6$; Fisher's exact test; $\alpha = 0.05$) in the present study (significance would require 5 out of 6 to fail).

The PC-Dr testing of computers weekly for six weeks following either fumigation or exposure to the control condition did not reveal substantial effects of fumigation (Table S5 in Supplementary material). Only sporadic failures of the optical drives occurred during pre-fumigation testing and during the first six weeks of post-fumigation testing. There was no statistically significant difference in the proportion of failed trials for any test detected between any fumigated computer group and the control group with the same power state using the z-test for proportions ($\alpha = 0.05$) in Sigmaplot 13.0. After the first six weeks,

computers were evaluated every 4–5 weeks with only sporadic optical drive failures until week 25 (Table S6 in Supplementary material).

After 20 weeks of operation, however, fumigated DVD $\pm$ RW drives began failing and producing grinding noises. Ultimately, five out six MB-fumigated and all six MI-fumigated drives failed BIT cycles (Fig. 2) and multiple PC-Dr tests (Fig. 3 and Table 2). The BIT cycle attempts to read the data from the DVD medium (i.e. disc) in the optical drive and compares them to a known correct version of the data stored locally, failing if the medium cannot be read or if the data does not match the known correct version (PassMark Software, 2017). The most consistently failed PC-Dr test was the DVD+R read write test, which tests the ability of the drive to write data to the DVD+R medium and then successfully read the data back. Other failed tests include seek tests, which test the ability of the drive to navigate between sectors on the disc, and the read compare tests, which compare two attempts to read the same portion of the disc (Williams, Personal communication). See Table S6 in Supplementary material for results of individual computers by PC-Dr test.

Failure was traced to soft rubber spacers that compress to hold the spindle motor and optical pickup assembly level while spinning the disc. The faulty spacers were cracked and likely unable to hold the spindle level, which resulted in grinding of the spindle platform on the disc (Fig. 4 and Figs. S18–S22 in Supplementary material). Six of twelve fumigated drives were repaired by replacing the spacers with those from unexposed drives. Repaired drives passed 1 trial of the DVD+R read write test immediately after repair and 3 trials on week 34 (Table S6 in Supplementary material). Cumulative BIT errors for repaired computers stabilized in the week following repair (Fig. 2) and PC-Dr test failures were reduced or eliminated in subsequent testing (Fig. 3). One failed drive could not be repaired and may have otherwise been damaged during troubleshooting (see Supplementary material). In the previous study using MB and chloropicrin, optical drives consistently failed PC-Dr tests due to mechanical problems. Rather than damage to an organic rubber material, failure was attributed to chloropicrin-induced corrosion of metal bearings and other moving parts (U.S. Environmental Protection Agency, 2012), which is significant since many electronic devices likely have similar motors or bushings.

Guidelines provided by the US Department of Agriculture and museum conservation authorities recommend against the fumigation of rubbers and sulfur-containing compounds with methyl bromide, cautioning that some materials can become malodorous; although references to specific reports of odor-related issues are not provided by these guidelines (Conservation and Art Materials Encyclopedia Online, 2016; U.S. Department of Agriculture, 2016). The fumigated computers in the current study were malodorous for several weeks during post-fumigation operation. The release of methylated byproducts and organosulfur compounds from fumigated rubber and building materials is evidence of its gas-phase reactivity with organic materials (Corsi et al., 2007; Hill et al., 1999), but no studies could be found on its effect on functional properties of materials.

The cost to repair equipment damaged by MB or MI fumigation would be site specific and depend on the type of equipment present. Given the impacts observed in the current study, the cost to repair damage to a data center or server facility, for example, might be negligible

if optical drives and computers displays are not present in large quantities. The cost to repair the corrosion induced failure of computer memory and hard drives, and the failure of metal motor-components reported after high-concentration chlorine dioxide fumigation (U.S. Environmental Protection Agency, 2010a; b, 2012), however, might be substantial. There are several studies that incidentally report no damage to common electronic equipment (computers, networking equipment, and audiovisual equipment) after fumigation with MB (Serre, Personal communication; Serre et al., 2015; U.S. Environmental Protection Agency, 2017b; Weinberg and Scheffrahn, 2006). The cost to repair damage to specialized equipment at hospitals or other infrastructure facilities is difficult to estimate since the equipment might use susceptible rubber materials for critical seals or bushings (Rahimi and Mashak, 2013), or other materials for which data is unavailable.

4. Conclusions

Fumigation with MB under the conditions tested only damaged rubber materials. Fumigation with MI altered the appearance of computer monitors, but did not limit their use in operating the computers. The small sample size makes it difficult to determine whether PSU failure was related to MB fumigation, but for screening fumigation methods for the potential widespread to damage electronic equipment, the test methods were suitable. Damage can be material specific however, so future lab and field-exercises should report the impact of fumigation conditions on a variety of electronic equipment even if only as an ancillary objective of the study. The delayed onset of optical drive failure due to deterioration of the rubber spacers highlights the importance of evaluating the long-term effects of decontamination methods on critical equipment during simulated use.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Effect of fumigation on sensitivity of U-10 RH sensors. White (before exposure) and grey (6 weeks after exposure) bars represent means and standard deviations of readings at 75% RH for 6 units. Asterisks indicate a significant difference detected using *t*-test (two-tailed, $\alpha = 0.05$) between before and after readings. Ctrl, fumigant-free control run; MB, methyl bromide fumigation; MI, methyl iodide fumigation.

Fig. 2.

Effect of (a) methyl bromide and (b) methyl iodide fumigation on the number of failed Burnin Test DVD $\pm$ RW drive cycles for each computer. Off and on refer to the power-state of the computer during fumigation. For most weeks five cycles were run per computer (one 8-h cycle per day). Weeks during which fewer than 3 cycles were completed are not plotted, but any failures occurring during those weeks are included in the cumulative total. Arrows represent times at which drives were repaired. Two control-condition computers had one failure and four had zero (data not shown).

Fig. 3. Effect of fumigation on the number of failed PC-Dr tests of the DVD $\pm$ RW drives. Ctrl, fumigant-free control exposure; MB, methyl bromide fumigated; MI, methyl iodide fumigated. Off and on refer to the power-state of the computer during exposure. Bars represent the sum of failed tests out of a total of 39 PC-Dr tests per computer each week except week 29 which was 37 tests. Arrow indicates drive was successfully repaired after testing. Arrow with x through line indicates repair failed and no further testing in subsequent weeks. Tests conducted before week 25 had sporadic failures and are listed in Tables S5 and S6 along with individual tests results for all computers.

Fig. 4.

Damage observed in failed DVD $\pm$ RW drives: (a) location of spacers (circled in red) in top down view of DVD $\pm$ RW drive with yellow arrow indicating location of disc spindle, (b) Intact spacer from control computer, (c) intact spacer from MB-fumigated computer showing deterioration, (d) spacers removed from an unexposed reference computer and (e) spacers removed from an MB-fumigated computer showing deterioration. Spacers were not removed from control computer to avoid accidental damage. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1

Temperature and relative humidity during fumigation and control conditions.

Condition	Bulk chamber ^a		Inside computers ^b			
	T, °C	%RH	Powered-on		Powered-off	
			T, °C	%RH	T, °C	%RH
Control ^c	29 (26–30)	79 (77–83)	29.3±0.03*	59 ±3	28.4 ±0.1	67 ± 4
methyl bromide	28 (28–29)	79 (68–81)	28.8±0.4*	80±3*	28.1 ±0.1	86.1 ± 0.3
methyl iodide ^d	28 (27–29)	73 (64–82)	29.1±0.4*	38 ±3*	28.1 ±0.1	49 ± 2

^aTime-weighted average (n = 2) and range of temperature.

^bIndividual time-weighted averages of temperature (T) and relative humidity (RH) inside each computer were calculated. Values are the average and standard deviation of these time weighted averages for either powered-on or powered-off computers (n = 3 except for the powered-off control which has n = 2).

^cRH measurements inside computers show unexpected downward bias.

^dRH measurements during methyl iodide fumigation showed an unexpected downward bias. Asterisk indicates a significant difference between powered-on and powered-off computers using *t*-test (two-tailed, $\alpha = 0.05$)

Table 2

Failed PC-Dr test of DVD $\pm$ RW drives on week 25.

PC-Dr test and (total number of trials per group) ^a	Total failed trials per group and (identifying number [s] [1–3] of computers with 1 failed trial)					
	Control		Methyl bromide		Methyl iodide	
	off	on	off	on	off	on
CD Read Compare (12)	0	0	1 (#2)	0	3 (#2)	0
CD Seek ^b (36)	0	0	3 (#2)	0	10* (#2)	0
CD-R Read Write (3)	0	0	2 (#2,3)	1 (#3)	1 (#2)	0
DVD Read Compare (12)	0	0	0	1 (#3)	4 (#2)	0
DVD Seek ^b (36)	0	0	3 (#2)	2 (#3)	12* (#2)	0
DVD+R Read Write (9)	0	0	6* (#2,3)	6* (#2,3)	3 (#2)	3 (#1,3)
DVD–RW Read Write (3)	0	0	1 (#2)	1 (#3)	0	0

^aThree computers per group with the equal number of trials per computer.^bResults of all seek test types (linear, random, and funnel) were combined for the CD and DVD media for each group. Asterisk indicates statistically significant difference between proportion of failed trials for a group and that of the corresponding control using Fisher's exact test ($\alpha = 0.05$). Only tests that failed are shown.