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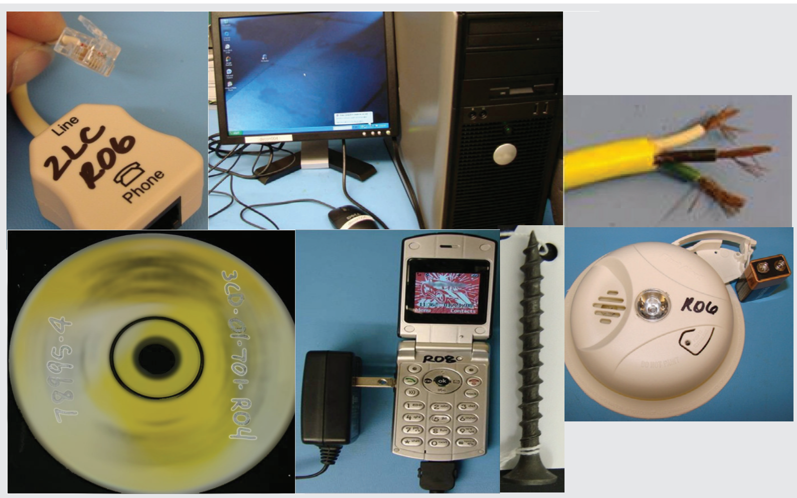
Compatibility of Material and Electronic Equipment with Chlorine Dioxide Fumigation

ASSESSMENT AND EVALUATION REPORT



Office of Research and Development
National Homeland Security Research Center

Compatibility of Material and Electronic Equipment with Chlorine Dioxide Fumigation

ASSESSMENT AND EVALUATION REPORT

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
NATIONAL HOMELAND SECURITY RESEARCH CENTER
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Disclaimer

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Foreword

The Environmental Protection Agency (EPA) holds responsibilities associated with homeland security events: EPA is the primary federal agency responsible for the country's water supplies and for decontamination following a chemical, biological, and/or radiological (CBR) attack. The National Homeland Security Research Center (NHSRC) was established to conduct research and deliver scientific products that improve the capability of the Agency to carry out these responsibilities.

An important goal of NHSRC's research is to develop and deliver information on decontamination methods and technologies to clean up CBR contamination. When directing such a recovery operation, EPA and other stakeholders must identify and implement decontamination technologies that are appropriate for the given situation. Decontamination strategies applied to high-value, historic, or sensitive items require use of technologies that are effective while causing minimal adverse effects on the native materials. This document provides information on the impact of a decontamination method - fumigation with chlorine dioxide gas - on materials and equipment including sensitive electronics.

NHSRC is pleased to make this publication available to assist the response community to prepare for and recover from disasters involving CBR contamination. This research is intended to move EPA one-step closer to achieving its homeland security goals and its overall mission of protecting human health and the environment while providing sustainable solutions to our environmental problems.

Gregory Sayles, Ph.D., Acting Director
National Homeland Security Research Center

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List of Acronyms and Abbreviations

AMI	American Media Incorporated
APPCD	Air Pollution Prevention and Control Division
AVI	Audio Visual Interleave
AWWA	American Water Works Association
BA	*Bacillus anthracis*
BI(s)	Biological Indicator(s)
BIOS	Basic Input/Output System
BIT	Burn-in Test
CBRTA	Chemical, Biological, and Radiological Technology Alliance
CD	Compact Disk
CD-ROM	Compact Disk - Read Only Memory
CD/DVD	Compact Disk/Digital Video Disk
CEM	Continuous Emissions Monitor
ClO_2	Chlorine Dioxide
CMOS	Complementary Metal-Oxide Semiconductor
COC	Chain of Custody
CODEC	Compression Decompression module
CPU	Central Processing Unit
CSI	ClorDiSys Solutions, Inc.
CT	The product of multiplying the factors Concentration and Time. Has the units of mass*time/volume
DCMD	Decontamination and Consequence Management Division
DHS	Department of Homeland Security
DI	Deionized
DIMM	Dual In-Line Memory Module
DNA	Deoxyribonucleic Acid
DOS	Disk Operating System
DQO(s)	Data Quality Objective(s)
DSL	Digital Subscriber Line
DTRL	Decontamination Technology Research Laboratory
DVD	Digital Video Disk
EDS	Energy Dispersive Spectroscopy
EMS	CSI Environmental Monitoring System
EMS/GMP	Environmental Monitoring System/Good Manufacturing Practices
EPA	U.S. Environmental Protection Agency
ESD	Electrostatic Discharge
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
GMP	CSI “Good Manufacturing Practices” ClO_2 generator system
GPU	Graphics Processing Unit
HCl	Hydrochloric Acid
HOBO®	Onset Computer Corp. RH and T data loggers
HSPD	Homeland Security Presidential Directive
IA&E	Independent Assessment and Evaluation
IPC	Industrial printed circuit (boards)
KI	Potassium iodide

KIPB	Phosphate buffered potassium iodide solution
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MEC	Material/Equipment Compatibility
N	Normality
NA	Not Applicable
N/A	Not available
NB	Nutrient Broth
NGA	National Geospatial-Intelligence Agency
NHSRC	National Homeland Security Research Center
NIST	National Institute for Standards and Technology
ON	The powered state of electrical equipment
OPA	Optical parametric amplifier
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
P&DC	Processing and Distribution Centers
PC	Personal Computer
PDA	Personal Digital Assistant
PDAQ	Personal Data Acquisition (System)
PEL	Permissible Exposure Limit
PVC	Polyvinyl chloride
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
RH	Relative Humidity
RTP	Research Triangle Park
S&T	Department of Homeland Security, Directorate for Science & Technology
SD	Standard Deviation
SEM	Scanning Electron Microscopy
SPI	Serial Peripheral Interface
SVGA	Super Video Graphics Array
T	Temperature
TSA	Tryptic Soy Agar
TWA	Time Weighted Average
USPS	United States Postal Service
WAL	Work Assignment Leader

List of Units

g	Gram
°F	Degree Fahrenheit
°C	Degree Celsius
L/min, Lpm	Liters per Minute
mg/L	Milligrams per Liter
mg/m^3	Milligrams per cubic meter
mL	Milliliter
ppb	Parts per Billion
ppm	Parts per Million
ppmv	Parts per Million by Volume

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Executive Summary

In response to Homeland Security Presidential Directive 10 (HSPD-10), the Department of Homeland Security (DHS) and the U.S. Environmental Protection Agency (EPA), through its National Homeland Security Research Center (NHSRC), coordinated to develop a comprehensive program to provide scientific expertise and evaluation of actual and future potential decontamination technologies that could be used to recover and restore buildings and sensitive equipment contaminated by biological warfare agents.

Chlorine dioxide gas (ClO_2) fumigation has been used successfully for the remediation of several federal buildings contaminated by *Bacillus anthracis* (*B. anthracis*) spores contained in letters. As part of an on-going evaluation of the chlorine dioxide decontamination method, this study was initiated by NHSRC and DHS and conducted at EPA's Decontamination Technology Research Laboratory (DTRL) in Research Triangle Park, North Carolina. The goal was to provide information on the effects of potentially corrosive ClO_2 gas on sensitive electronic components and materials, which substituted for the types of components also found in high-end military and commercial equipment such as medical devices and airport scanners.

Four categories of materials were defined by the principal investigator. Not included in this study were Category 1 materials, which are structural materials with a large surface area inside a typical building. While the field experience and subsequent NHSRC laboratory testing have clearly demonstrated that these materials in the building can have a significant effect on the ability to achieve and maintain the required concentration of fumigant, fumigation has not been shown to affect their functionality.[13] The three categories examined in this study were:

- Category 2 Materials included low surface area structural materials that were expected to have minimal impact on the maintenance of fumigation conditions during the decontamination event; however, their functionality and use may be affected by the fumigation.
- Category 3 Materials included small, personal electronic equipment.
- Category 4 Materials included desktop computers and monitors.

By using visual inspection and tests on equipment function, this study documented the effects of different fumigation conditions on the ClO_2 fumigation of three categories of materials and equipment commonly found inside large buildings and offices. Equipment and materials were subjected to a variety of fumigation conditions. The standard fumigation condition, defined as 3,000 parts per million by volume (ppmv) chlorine dioxide with 75 percent relative humidity (RH), is the basis for remediating sites contaminated with *B. anthracis* spores.

Other fumigation conditions included:

- 75 ppmv ClO_2 at 75 percent RH (applicable to non spore-forming organisms)
- 75 ppmv ClO_2 at 40 percent RH
- 3,000 ppmv ClO_2 at 90 percent RH.

Exposures to 40 percent and 90 percent RH without chlorine dioxide were performed to determine the effect of RH alone.

The observed effects were a direct function of the conditions to which the material or equipment was exposed. Fumigation at levels of RH exceeding standard fumigation conditions (i.e., 75 percent RH) resulted in the most significant impacts. In general, the effects were directly related to the ClO_2 concentration, RH, and type of material or equipment exposed.

Results obtained in this study show that RH during fumigation should be maintained between 65 percent and 75 percent to maximize compatibility for most materials.

Effects of fumigation for each category of material/equipment are summarized below:

Category 2:

- No visual or functional changes were noted for 300 series stainless steel, laser-printed paper, or gaskets under any of the test run conditions.
- The screws on the circuit breakers and the inkjet printed paper were affected at every condition, including the tests with only high humidity (no ClO_2). The high ClO_2 and high humidity (>88 percent) resulted in the most corrosion of the screw and fading of the inkjet paper.
- The exposure to only high humidity affected the circuit breaker screw (mild corrosion) and inkjet paper (very mild fading). Any additional effects noted for these and other materials at the other test conditions were due to the combination of ClO_2 and humidity.

- Visual changes to other materials were a function of the ClO_2 concentration and RH.
  - At low concentration and low RH no additional materials were impacted.
  - Increasing the humidity to 75 percent resulted in severe corrosion of the low carbon steel, tarnishing of the copper, yellowing of the photographs, mild corrosion of the drywall nails and screws.
  - At the higher ClO_2 concentration, the impacts noted above were predominantly exacerbated for most material. Increasing the humidity further at the high ClO_2 concentration further increased the deleterious visual impacts noted.
  - The presence of condensation during fumigation also resulted in corrosion of 430 stainless steel, discoloration of wiring and a chalky residue on aluminum. These impacts were a direct result of the combination of ClO_2 with a condensing humidity environment, as such impacts were not observed in the presence of condensation alone.
- The corrosion on metals, as noted above, resulted in unstable or unreliable resistance measurements.
- The smoke detector was only impacted by fumigation at condensing humidity; the addition of ClO_2 seemed to exacerbate the impact.
- The light switch fumigated with ClO_2 at the higher temperature and condensing humidity had intermittent failures.

Category 3:

- There were no visual or functional changes noted for the Personal Digital Assistants (PDAs) under any fumigation conditions.
- Mild discoloration of the cell phone screen occurred at standard fumigation conditions in this project (3,000 ppmv ClO_2 and 75 percent RH).
- The presence of ClO_2 and condensing humidity resulted in fading of the cell phone screen, severe corrosion on the fax machine printer bar, and damages to both the compact disk (CD) and digital video disk (DVD). At lower humidity (75 percent and below) and lower ClO_2 concentration, these impacts were not observed. Typical ClO_2 fumigation conditions do not reach such a high RH.

Category 4:

- Power state of the computer did seem to have an effect on the material compatibility. The higher internal temperatures of ON (powered) computers reduced the internal RH and mitigated some effects of fumigation. Reducing the internal humidity also reduced effectiveness of fumigation against biological indicators (BIs) inside the computer.
- The presence of ClO_2 in the atmosphere and humidity of at least 75 percent resulted in corrosion of the stamped metal grid on the back of the computer, wire discoloration, corrosion of the plug, and the formation of a white dust due to interaction of the ClO_2 with one of the heat sinks (nickel-coated aluminum). The dust formation was not observed on the other aluminum heat sink, making the alloy very important to the impacts observed. Greater amounts of dust were formed at higher ClO_2 concentrations and higher RH values. This dust may cause human health effects and must be removed.
- Optical plastics were damaged in the CD/DVD drive by 3,000 ppmv ClO_2 and RH inside the computer greater than 75 percent.

Materials with the potential for damage include, but are not limited to, the following:

- Unpainted and unlubricated carbon steel.
- Ferritic and martensitic chromium alloys of stainless steel (Type 400 series).
- Certain alloys of aluminum.
- Devices with exposed copper contacts, including battery-powered devices.
- Any device with optical plastic components, such as consumer-grade cameras, CD/DVD drives, laser pointers.
- Equipment containing extensive color-coded wire insulation.

1.0 Project Description and Objectives

Chlorine dioxide gas (ClO_2) was used to decontaminate two of the United States Postal Service Processing and Distribution Centers [Curseen-Morris (former Brentwood Road facility, Washington, D.C.) and Trenton (Hamilton Township, N.J.)], as well as the American Media Inc. (AMI) facility in Boca Raton, FL., as part of remediation activities following the delivery of letters contaminated by *B. anthracis* (BA) spores in the fall of 2001.[1] The success of the building decontaminations for BA spores and subsequent laboratory work by NHSRC has produced substantial data regarding the efficacy and practicality of the use of ClO_2 for the decontamination of high-threat biological agents.[2-4]

While no significant impacts on building structural materials have been determined in recent NHSRC work[5, 6] no specific data related to the impact of decontamination on electronic equipment have previously been published with respect to homeland security-related decontamination. Data on the effect of decontamination on electronic equipment are needed to further define guidelines on the selection and use of ClO_2 for building and equipment decontamination, especially related to restoration of critical infrastructure. This project was performed to provide such information.

1.1 Purpose

The main purpose of this work was to provide information to decision makers about the potential impact, if any, of the ClO_2 decontamination process on materials and electronic equipment. This effort looked at the impact on the physical appearance, properties, and functionality of certain types of materials and equipment. While the impact on specific items was addressed, the purpose was to also consider some items, particularly the computer systems and electronic components, as substitutes for high-end equipment such as medical devices and airport scanners. The laser diode in a DVD drive, for instance, is similar to laser diodes found in equipment ranging from fiber optic systems, deoxyribonucleic acid (DNA) sequencers, range finders, and directed energy weaponry to industrial sorting machines.

1.2 Process

In order to investigate the impact of ClO_2 gas on materials and equipment under specific fumigation conditions, material was divided into categories: These categories are described in sections 1.3, 1.3.1, 1.3.2, and 1.3.3. Category 1 materials were not addressed during this study. Materials in Categories 2 and 3 were evaluated in-house before and for one year after the date of exposure. Category 4 materials were evaluated in-house before and immediately after fumigation. The sample set was then divided with one of the triplicate samples being sent to Alcatel-Lucent for in-depth analysis. The other two samples remained for in-house evaluation over the course of a year.

Due to its instability, ClO_2 gas must be generated on site by two primary methods (as discussed later, section 1.2.1). This laboratory-scale investigation was pertinent to the process gas (i.e., ClO_2, at defined concentrations, in the absence of detectable Cl_2) and fumigation conditions (i.e., time, temperature and RH); the results are not intended or expected to be specific to a particular ClO_2 generation method. A brief description of the ClO_2 fumigation process for decontamination of facilities is presented below, as well as an overview of the laboratory facility in which the testing was performed.

1.2.1 Overview of the ClO_2 Fumigation Process

Fumigation with ClO_2 under conditions that have been shown to be effective in other efforts for the decontamination of biological threats on building material surfaces was the process investigated in this study. In past fumigation events for *B. anthracis* decontamination, the conditions set by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) crisis exemptions required that a minimum concentration of 750 ppmv be maintained in the fumigation space until a minimum multiplication product of concentration and time (CT) of 9,000 ppmv-hours was achieved.

Other important process parameters included a minimum temperature of 24 °C (75 °F) as a target and a minimum RH of 75 percent. While the minimum effective CT has been maintained in subsequent events, substantial improvement in the ClO_2 fumigation process technology allowed for higher concentrations to be achieved in large buildings. At the commencement of this testing, the standard practice for fumigation with ClO_2 for *Bacillus* spores had been moving toward a concentration of 3,000 ppmv within the volume for three hours to achieve the CT of 9,000 ppmv-hr.[7]

While these conditions (9,000 ppmv-hours, 24 °C, 75 percent RH) have been required for the decontamination of facilities contaminated with BA spores, NHSRC research and field events have suggested that effective inactivation of other biological agents (e.g., viruses, vegetative bacteria, fungal spores, biotoxins) may be achieved at much lower concentrations and CT values.[8] Field observations have suggested that 75 ppmv for 12 hours, a total of 900 ppmv-hr, may be effective for decontamination of facilities lightly contaminated with mold.[9] NHSRC research has shown complete inactivation of the vaccinia virus and vegetative bacteria at CT values less than 50 ppmv-hours at 75 percent RH (75 ppmv for 30 minutes, depending on organism and material).[10]

Relative humidity is an important factor in the inactivation of BA spores with ClO_2 gas.[2] Due to the lack of information on the impact of RH on the effectiveness of ClO_2 gas against other agents, studies are currently being performed. For BA spores on building materials, the effectiveness of the gas drops off significantly below 75 percent RH; conversely, the CT required for a six log reduction in spores decreases dramatically at higher RH.[2]

ClO_2 is commercially generated by two methods. The wet method, such as the one used by Sabre Technical Services, LLC. (Slingerlands, N.Y.; http://www.sabretechservices.com), generates the gas by stripping ClO_2 from an aqueous solution using emitters. The liquid ClO_2 is generated by reacting hydrochloric acid (HCl), sodium hypochlorite and sodium chlorite between pH 4.5 to 7.0. Sabre Technical Services was the contractor for all fumigations related to the BA spore decontaminations to date (with the exception of the State Department mail facility [SA-32] which was fumigated with vapor-phase hydrogen peroxide) and are currently continuing to improve their process through use for mold remediation of facilities in New Orleans. Sabre has fumigated structures as large as 14,000,000 cubic feet (USPS facility, former Brentwood Processing and Distribution Center) at CTs in excess of 9,000 ppmv-hr.[11]

The dry method, such as that used by ClorDiSys Solutions, Inc. (Lebanon, N.J.; http://www.clordisys.com), passes a dilute chlorine gas (i.e., 2 percent in nitrogen) over solid hydrated sodium chlorite to generate ClO_2 gas. ClorDiSys has performed several low level fumigations (~100 ppmv for a total of ~1200 ppmv-hours) of facilities for non-spore-forming organisms, and their technology is used widely in sterilization chambers.[12] No differences in the effectiveness of either of the two generation techniques to inactivate BA spores on building materials have been observed in laboratory-scale investigations. Note that the wet technology is potentially "self humidifying", while the dry technique requires a secondary system to maintain RH. There are significant differences in experience in the scale of field operations, as well as in generation capacity and state of advancement of technology application to large structures.

1.2.2 Laboratory Facility Description

The material compatibility testing was performed in the EPA's National Homeland Security Center (NHSRC), Decontamination Consequence Management Division's (DCMD's) Decontamination Technologies Research Laboratory (DTRL) located in Research Triangle Park, N.C. This facility is equipped with a ClorDiSys Solutions, Inc. (CSI), Good Manufacturing Practices (GMP) gas generation system, ClO_2 gas generation system and ancillary sampling/monitoring equipment, test chambers, and support equipment. The GMP automatically maintains a constant target ClO_2 concentration in an isolation chamber and injects ClO_2 (20 liters per minute (L/min) of ideally 40,000 ppmv ClO_2 in nitrogen) when the concentration inside the isolation chamber falls below a preset condition. The isolation chamber is maintained at a set ClO_2 concentration, temperature, and RH; this reservoir is used as the supply of a constant ClO_2 concentration to several experimental setups (e.g., kinetics test chamber, material/equipment compatibility test chamber, permeation test system, adsorption test bed) within DTRL. The ClO_2 concentration inside the isolation chamber is measured by the CSI gas generation system via a photometric detector located in the GMP unit, providing feedback to the generation system. A similar ClorDiSys Solutions, Inc. environmental monitoring system (EMS™) photometric detector (Lebanon, N.J.; http://www.clordisys.com) is used for ClO_2 monitoring in test chambers or setups as required by specific test protocols.

Other measurement capabilities within DTRL include Dräger Polytron 7000 (Draeger Safety, Inc., Pittsburgh, PA) remote electrochemical sensors (ClO_2/Cl_2), a Hach AutoCAT 9000™ Amperometric Titrator (Hach Company, Loveland, Colo.) (to facilitate wet chemical analysis for ClO_2 concentration measurements via a modification of American Water Works Association (AWWA) Standard Method 4500-ClO_2 E. Amperometric II), an Interscan Corporation (Chatsworth, California) LD233 dual range ClO_2 monitor (0-200 ppb; 0-20 parts per million [ppm]), and an ion chromatograph (DX-120; Dionex, Sunnyvale, CA) for use with the Occupational Safety and Health Administration (OSHA) ID-202 method, "Determination of Chlorine Dioxide in Workplace Atmospheres." Method ID-202 was not used during this particular study.

This task required that materials, computers, and other potentially sensitive equipment be exposed to ClO_2, at conditions shown to be effective for decontamination of biological and chemical agents on building materials and/or in facilities, in order to assess the impact (hence, compatibility) of the fumigation process on the material/

equipment. Two identical isolation chambers (material/equipment compatibility chambers or MEC chambers) were used for these compatibility tests. The MEC control chamber was never exposed to fumigant and was used for control blanks only. The MEC test chamber served as the isolation chamber for the fumigant-exposed material/equipment. Figure 1-1 shows the dimensions of the MEC chambers; a photograph of the MEC test chamber is shown in Figure 1-2. Power is supplied within the chambers by the inclusion of two seven-outlet surge protectors [BELKIN seven-outlet home/office surge protector with six-foot cord, Part # BE107200-06 (Belkin International, Inc.; Compton, CA)] inside each chamber (not shown in Figure 1-1). The power cord from each surge protector penetrated the polyvinyl chloride (PVC) chamber material on the bottom back wall of the chamber and was sealed to the chamber to prevent the fumigant from leaking out.

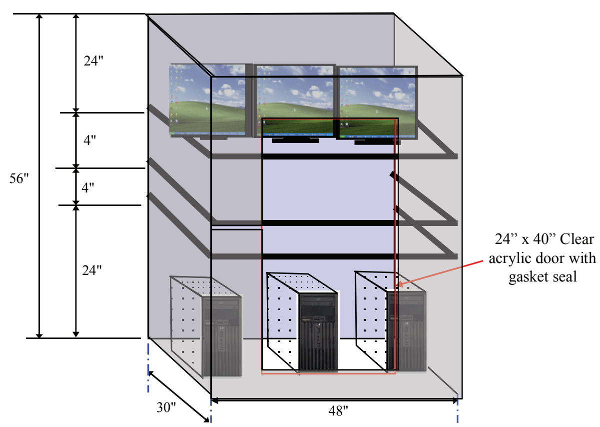


Figure 1-1. Schematic diagram of the MEC Chambers.

Figure 1-2. Photograph of the MEC Test Chamber.

The chambers are made of opaque PVC with a clear acrylic door, which is fastened with a bolted flange. The door is covered with an opaque material during tests to prevent light-catalyzed reactions from taking place during exposure. The three removable shelves within the chamber are made of perforated PVC. Grounded woven wire mesh (Type 304 Stainless steel, 0.011" gauge wire) was placed on each shelf to dissipate any potential static electricity. The ground wire penetrated the chamber wall and was attached to the electrical service ground. Three fans were placed in each chamber to facilitate mixing.

1.3 Project Objectives

The objective of this work was to assess the impact of fumigation with ClO_2 at conditions known to be effective for decontamination of materials and/or facilities contaminated with specific biological or chemical threats, on materials, electrical circuits, and electronic equipment.

The fumigation impact was investigated for:

- Fumigant concentration (none, low and high).
- RH (low, standard and high).
- Power state of the equipment (OFF or ON).

Three categories of material and equipment were tested at the different fumigation conditions discussed in detail in Section 3 (and listed in Tables 3-5 and 3-6); the categories can be separated based upon the conditions of testing and analysis performed to assess the impacts.

Category 1 materials are structural materials with a large surface area inside a typical building. While the field experience and subsequent NHSRC laboratory testing have clearly demonstrated that these materials in the building can have a significant effect on the ability to achieve and maintain the required concentration, fumigation has not been shown to affect their functionality.[13] This type of material was not included in this study. The three categories that were investigated are described below.

1.3.1 Category 2 Materials

Category 2 Materials include low surface area structural materials which are expected to have minimal impact on the maintenance of fumigation conditions within the volume. However, the functionality and use of Category 2 materials may be impacted by the fumigation event. The objective for this category of materials was to assess the visual and/or functional (as appropriate) impact of the fumigation process on the materials. The impact was evaluated in two ways. First, through visual inspections at each fumigant condition (concentration, temperature, RH, and time), which were directed toward possible locations suspected of corrosion and possible material defects due to the fumigation process. Second, functionality was assessed, as appropriate, for the material: resistance was measured for coupons and stranded wires; circuit breakers and copper and aluminum services were overloaded to determine the time prior to tripping the breaker; sealants were checked for leaks; gasket elasticity was tested with a simple stress test; lamps were tested to see if the bulb would light; the digital subscriber line (DSL) conditioner was tested for transmission on a telephone or fax; and the smoke detector batteries and lights were checked and were put through a smoke test. Printed documents and pictures were inspected for possible alteration of their content.

The visual inspections were documented in writing and by digital photography for each material prior to and after exposure in each fumigation event. Functional testing of materials was assessed prior to and post-ClO_2 treatment, then monthly for five months, and again at year's end. Table 1-1 lists specifics of these materials and details the post-test procedures, where applicable. With reference to the "Post-Fumigation Testing Description" column of Table 1-1, "where applicable" means that certain items were not tested for functionality after exposure. The entry "not tested" is used in these cases.

Table 1-1. Category 2 Material Information and Post-Fumigation Testing Description

Material Name	Sample Dimension / Sample Size	Description	Post-Fumigation Testing Description
Type 3003 Aluminum	2" x 2" x 0.0625" / 3 pieces	Metal Coupon	Triplicate coupons were stacked and the resistance was measured between the top and bottom coupon using an ohm meter.
Alloy 101 Copper	2" x 2" x 0.64" / 3 pieces		
Low Carbon Steel	1.5" x 2" x 0.0625" / 3 pieces		
Type 304 Stainless Steel	2" x 2" x 0.0625" / 3 pieces		
Type 309 Stainless Steel	1.5" x 2" / 3 pieces		
Type 316 Stainless Steel	2" x 2" x 0.0625" / 3 pieces		
Type 410 Stainless Steel	2" x 2" x 0.0625" / 3 pieces		
Type 430 Stainless Steel	1" x 2" x 0.012" / 3 pieces		
Yellow SJTO 300 VAC Service Cord[1]	NA / 3 pieces	Stranded Wire	The resistance of each wire was measured and recorded.
Silicone Caulk	Approximately 1" bead on the inside of a rectangular box	Sealant	Water was run into the corner of the outlet box with the sealant and the box was observed for leaks.
Gasket	0.125" thick flange foam rubber / 3 pieces	-	Gasket was folded in half and examined for cracks.
Incandescent Light	NA / 3 pieces	Switch	A halogen light bulb was placed into the socket and the lamp was turned on. If the lamp failed to light the bulb, a new bulb was tested to verify that the switch was inoperable.
DSL Conditioner	NA / 1 piece	-	Simple connectivity was tested using a laboratory telephone through the conditioner.
Drywall Screw	1.625" coarse thread / 3 pieces	-	Not tested.
Drywall Nail	1.375" coated / 3 pieces	-	Not tested.
Copper Services	NA / 3 pieces	Copper and Aluminum Services	Services were tested at 15 amps (150% capacity) and timed to failure.
Aluminum Services	NA / 3 pieces		
Circuit Breaker	NA / 10 pieces	-	Breakers were tested at 20 amps (200% capacity) and timed to failure.

Material Name	Sample Dimension / Sample Size	Description	Post-Fumigation Testing Description
Smoke Detector	NA / 1 piece	-	Battery was tested by pressing the button on the detector. In the hood, the alarm was tested by spraying the "Smoke Check-Smoke Alarm Tester" directly at the alarm. The light was checked to see if it was functioning.
Steel Outlet/Switch Box	2" x 3" x 1.5" / 1 piece	-	Not tested.
Laser Printed Paper[2]	8.5" x 11" (15 pages)	-	Not tested.
Ink Jet Colored Paper[2]	8.5" x 11" (15 pages)	-	Not tested.
Color Photograph	4" x 6" / 3 pieces	-	Not tested.

Note:'- ' indicates Material Name and General Description are the same and 'NA' = not applicable.
[1]The outside of the cord served as Housing Wire Insulation, and the three-stranded interior wires served as the Stranded Wires.
[2]Test page can be found in Appendix E of the EPA Quality Assurance Project Plan (QAPP) entitled, "Compatibility of Material and Electronic Equipment with Chlorine Dioxide Fumigation," dated July 2007.
NA – not applicable

1.3.2 Category 3 Materials

Category 3 Materials include small, personal electronic equipment. The objectives for this category were to determine aesthetic (visual) and functionality impacts on the equipment as a function of time post-fumigation. The assessment of the impact was visual inspection for aesthetic effects and evaluation of functionality post-fumigation. Inspection occurred monthly for five months, and then again at the one-year period, with the equipment stored at monitored (logged) ambient conditions throughout that time period. Visual inspections of the equipment were documented in writing and by digital photographs. Any indications of odor emissions were also documented. Further, the functionality of each piece of equipment was assessed comparatively with similar equipment that was not subjected to the fumigant exposure. Category 3 materials are listed in Table 1-2 and Table 1-3 details the post-test procedures.

Table 1-2. Category 3 Materials

Materials	Description	Manufacturer	Model Number	Sample Size
Personal Digital Assistant (PDA)	Handheld	Palm	Z22	1 piece
Cell Phone	Pay-as-you-go Super thin flip superphonic ringtones full color screen	Virgin (Kyocera)	Marbl	1 piece
Fax/Phone/ Copier Machine	Plain-paper fax and copier with 10-page auto document feeder and up to 50-sheet paper capacity. 512KB memory stores up to 25 pages for out-of-paper fax reception	Brother	Fax 575	1 piece
Data DVD	Standard 21331 DVD Video	Warner Brothers		1 piece
Data CD	Standard Audio CD	CURB Records		1 piece

Table 1-3. Post-Fumigation Testing Procedures for Category 3 Materials

Material	Description of Testing Procedure
PDAs	The import and export capabilities were tested, and the screen condition was noted. Keypad and screen conditions were noted.
Cell Phones	Incoming and outgoing call capabilities were tested by ring and audio functions. Keypad and screen conditions were noted.
Fax Machines	Incoming and outgoing fax capabilities were tested, as were incoming and outgoing call functions.
DVD	The audio and visual functions were tested.
CD	The audio functions were tested by playing the first 10 seconds of each song.

1.3.3 Category 4 Equipment

The assessment of the impact of fumigation on Category 4 equipment was done in conjunction with Alcatel-Lucent. This assessment was performed through LGS Innovations, Inc. as the prime performer of a Chemical, Biological, and Radiological Technology Alliance (CBRTA) Independent Assessment and Evaluation (IA&E). The IA&E through CBRTA was funded by EPA and the Department of Homeland Security S&T (Directorate of Science & Technology) via interagency agreements with the National Geospatial-Intelligence Agency (NGA, the executive agency for CBRTA at the time of the study).

Category 4 equipment includes desktop computers and monitors. The objective of testing for this category of equipment (and materials) was to assess the impact of the fumigation conditions using a two- tiered approach: (1) visual inspection and functionality testing using a personal computer (PC) software diagnostic tool, and (2) detailed analysis for a sub-set of the tested equipment through the CBRTA IA&E. The computer systems not sent for detailed analysis from each test set remained at the EPA facility. Each of these computers was put through a burn-in test (BIT) sequence five days a week, for eight hours a day, to simulate normal working conditions. For all computer systems, PC-Doctor® Service Center™ 6 (PC-Doctor, Inc.; Reno, NV) was run as the PC software diagnostic tool. The BIT sequence and PC-Doctor® Service Center™ 6 protocols were developed by Alcatel-Lucent specifically for this testing.

While the impact on computer systems was being assessed directly in this effort, the purpose of the testing was to consider the systems as surrogates to provide many of the components common to high-end equipment (e.g., medical devices, airport scanners). Hence, the detailed analysis was a critical component of this testing. The objective was to identify components and specific parts of components that may be susceptible to corrosion because of the fumigation process. This information can then be used to make informed decisions about the compatibility of other equipment that may have similar components (at least similar in operation) and can reduce further testing or uncertainty in the field application. All equipment and materials listed below were selected by Alcatel-Lucent as appropriate test vehicle sets to meet the objectives of this testing. Table 1-4 lists the Category 4 equipment and materials included in these tests

Table 1-4. Category 4 Tested Materials

Computer Component	Description	Additional Details
Dell™ OptiPlex™ 745 desktop computer		See Appendix A for specifications.
Dell™ 15 inch flat panel monitor		See Appendix A for specifications.
USB keyboard and mouse		
Super Video Graphics Array [SVGA]		
Metal coupons	Silver (Ag) Copper (Cu) Aluminum (Al)	These metals are used extensively in fabricating desktop computers.
Cables	Computer power cord Monitor power cord Analog video cable	
Industrial printed circuit board (IPC)		

Further objectives in this study for Category 4 equipment and materials were to (1) provide an indication if localized conditions in an operating computer may be different from the bulk of the chamber and (2) obtain an indication of the potential impact the local conditions may have on the effectiveness of the ClO_2 fumigation process to inactivate BA spores potentially located within the computer. For the first part of this objective, process parameter measurements in the bulk chamber and within the computers were compared. For the second part, biological indicators (BIs) were used to provide an indication of the effectiveness of the fumigation in the bulk chamber and within each computer. BIs have been shown not to correlate directly with achieving target fumigation conditions for BA spores or inactivating BA spores on common building surfaces.[14] While BIs do not necessary indicate achievement, they will sufficiently indicate a failure to achieve successful conditions.

The locations of process measurement monitors, metal coupons, IPC board and BIs within each computer are shown in Figure 1-3. The HOBO® (U12-011, Onset Computer Corporation, Pocasset, MA) is a relative humidity and temperature monitor with a built-in data logger. The placement of these items within the computers was decided based upon the air flow within the chamber and the desire not to affect the operation of the computer. The items were affixed to the inside of the side panel of the computer case using self-adhesive hook-and-loop dots (P/Ns 9736K44 and 9736K45, McMaster-Carr, Atlanta, GA).

Figure 1-3. Location of HOBO®, Metal Coupons, IPC Board, and BI within the Computers (left side panel shown from a top-down view with respect to the computer).

2.0
Experimental Approach

2.1 DTRL Chlorine Dioxide Analytical Capabilities

DTRL ClO_2 measurement capabilities include six analytical techniques that were assessed separately or on one-to-one basis depending on the type of measurement needed (continuous versus extractive). The six available techniques are listed in Table 2-1.

Table 2-1. Available Chlorine Dioxide Analyses

Manufacturer/ Organization	Method	Title	Equipment
CSI			Model GMP photometric monitor
CSI			Model EMS photometric monitor
AWWA	Standard Method 4500-ClO_2 E Modified	Amperometric II	
Interscan	Electrochemical Voltametric CEM		LD233
Dräger			Model Chlorine electro-chemical sensor with Polytron 7000 transmitter
OSHA	ID-202	Determination of Chlorine Dioxide in Workplace Atmospheres	

Among the six measurement techniques, the CSI photometric monitors are applicable to the high concentration included in the test matrices (3,000 ppmv). The Interscan LD233 was used with a 10:1 dilution for the 75 ppm ClO_2 tests. The modified Standard Method 4500-ClO_2 E was used for both concentrations. The OSHA ID-202 was not used during this study while the Dräger Polytron 7000 sensors were used only for safety (i.e., room monitor). Additional details on the photometric monitors, modified Standard Method 4500 ClO_2 E, and the Interscan LD233 will be found in sections 3.1.1 through 3.1.3.

2.2 General Approach

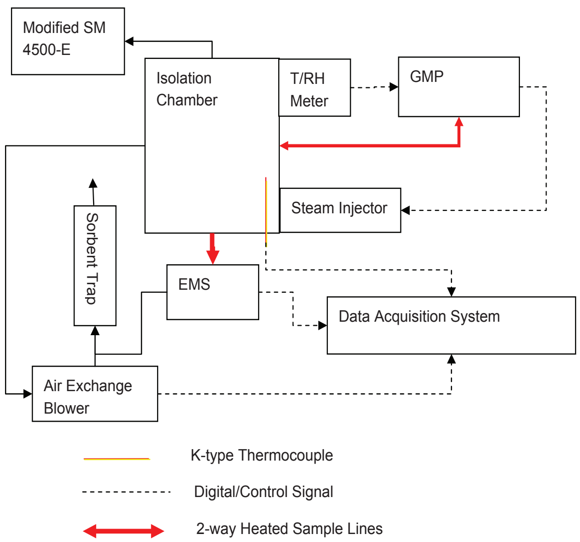
The effect of the fumigation process on materials and electronic equipment was investigated using visual inspection and an assessment of functionality. All visual inspections were documented in writing and with digital photographs. Functionality testing was documented in writing (and by digital photography, where appropriate). Additionally, a subset of Category 4 test sets was subjected to a detailed IA&E by Alcatel-Lucent and was detailed in their final report, "Assessment and Evaluation of the Impact of Chlorine Dioxide Gas on Electronic Equipment," dated May 23, 2008.[15]

The impact of the fumigant on the material and electronic equipment was investigated at different fumigation conditions (concentration, temperature, RH, and exposure time). The MEC control and test chambers were both maintained at the same temperature, RH and air exchange rates. The MEC control chamber was never exposed to ClO_2.

2.3 Sampling Strategy

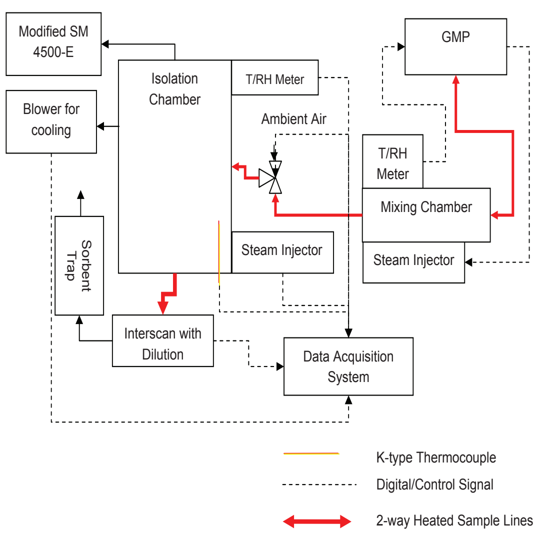
The test matrices include tests at two different fumigant concentrations (3,000 ppmv and 75 ppmv). The two different concentrations required that two different sampling and measurement techniques be used to monitor the chamber concentrations. The 3,000 ppmtarget ClO_2 concentration was directly controlled with the GMP, as shown in Figure 2-1. The 75 ppmv target was achieved using a mixing chamber (i.e., GMP Box), as shown in Figure 2-2. The mixing chamber was established at the desired temperature and RH and controlled at 3,000 ppmv by the GMP. The MEC test chamber inlet flow was divided between gas from the mixing chamber (at 3,000 ppmv) and ambient air. ClO_2 injection from the mixing chamber was controlled via a feedback loop with measurement in the MEC test chamber using the Interscan LD233 ClO_2 monitor (0-20 ppmv range). The Interscan LD233 unit pulled a 500 cc/min sample diluted 10:1 nominal) that included 450 cc/min clean air controlled by a mass flow controller (Tylan FC-260V, Nextron, Seoul, Korea), with the difference continually pulled from the MEC test chamber.

Modified Standard Method 4500-ClO_2 E samples were taken every 30 minutes to confirm the concentration of ClO_2 in the MEC test chamber for both the high and low concentration tests.



EMS – CSI Environmental Monitoring System
SM – Standard Method
T/RH – Temperature/Relative Humidity
GMP – CSI "Good Manufacturing Practice" ClO_2 generator

Figure 2-1. Experimental Setup of the MEC Test Chamber: 3,000 ppmv Scenario.



SM – Standard Method
T/RH – Temperature/Relative Humidity
GMP – CSI "Good Manufacturing Practice" ClO_2 generator

Figure 2-2. Experimental Setup of the MEC Test Chamber: 75 ppmv Scenario.

The CSI GMP Box was configured for RH control using either the ClorDiSys GMP or LabVIEW (Version 8; National Instruments, Austin, TX). In each case, a Vaisala Temperature/Relative humidity (T/RH) sensor (HMD40Y; Vaisala, Helsinki, Finland), checked for proper operation at the beginning of each test, provided a signal used in a feedback loop. When the Vaisala T/RH sensor read lower than the RH set point, solenoid valves were opened to inject humid air from a gas humidity bottle (LF-HBA; Fuel Cell Technologies Inc., Albuquerque, NM). The gas humidity bottle was heated to 60 °C to create a warm air stream saturated with water vapor. The GMP Box typically remained at ambient temperature, for there is no major heat source inside. In cases where a condition above ambient temperature was desired, the temperature of the GMP Box was controlled by the LabVIEW temperature control module operating a ceramic infrared lamp (ESES; Mor Electric Heating Association, Inc., Comstack Park, MI). The steam injectors were preheated to prevent any condensation.

The MEC test and control chambers needed to be cooled because of the heat generated by the operating equipment inside. If sufficient, all cooling was done by controlling the air exchange rate in order to prevent any cold spots within the chamber. A blower was used to exhaust air from the chambers and pull in cooler air. The blower also operated to prevent over-pressurization of the isolation chamber. With the higher heat input of operating computers, additional cooling was necessary: cooling water above the dew point was circulated through cooling fins inside the chamber.

2.4 Sampling/Monitoring Points

The testing strategy for the impact of the fumigation process on material and electronic equipment required monitoring the fumigation environment in both chambers (MEC test and control) and inside the computers for the testing of Category 4 equipment. Both the MEC test and control chambers were conditioned and controlled to provide the same temperature and RH for the entire fumigation event.

Local variations in temperature were expected, especially due to the heat output of electronic devices while operating. This variation in temperature also affected RH. Because RH was a critical parameter in the effectiveness of the fumigant, the RH was checked by placing multiple HOBO® T/RH sensors in and near fumigated equipment. The location of the sensors within the computers is shown in Figure 1-3. Each of the HOBO® sensors was checked against both a Vaisala T/RH sensor used as a reference (never exposed to fumigant) and the Vaisala T/RH sensor used to measure the bulk RH in the chamber in order to obtain direct comparisons between the bulk and the localized RH after correcting for individual sensor bias. The monitor points within the computers allow determination of temperature and RH gradients that might exist; the target temperature, RH, and ClO_2 concentration is that of the bulk chamber (e.g., not within equipment). The HOBO® sensors logged RH and temperature in real time, and the data were downloaded after the fumigation event was complete.

2.5 Frequency of Sampling/ Monitoring Events

Table 2-2 provides information on method, test location, sampling flow rates, concentration ranges, and frequency for the measurement techniques used.

Table 2-2. Monitoring Methods

Monitoring Method	Test Location	Sampling Flow Rate	Concentration Range ClO_2 (ppmv)	Frequency and Duration
GMP ClO_2 Monitor	MEC test chamber (3,000 ppmv tests); GMP Box (75 ppmv tests)	5 Lpm nominal	50-10,000	Real-time; 4 per minute
EMS Monitor	MEC test chamber (3,000 ppmv tests); GMP Box (75 ppmv tests)	5 Lpm nominal	50-10,000	Real-time; 6 per minute
Modified Standard Method 4500-ClO_2 E	MEC test chamber; GMP Box	0.5 Lpm	36 -10,000	Every 60 minutes; 4 minutes each
Interscan	MEC test chamber (75 ppmv tests)	0.5 Lpm nominal	0-20 (undiluted) 0-200 (with dilution system)	Real-time; 6 per minute
Vaisala T/RH sensor	MEC test chamber; GMP Box	NA	0-100 % RH, -40 to 60 °C	Real-time; 6 per minute
HOBO® U10 T/RH meter	MEC test chamber, Inside Category 4 chassis	NA	5-95% RH, -20 to 70 °C	Real-time; 6 per minute

NA – not applicable

to reach the target concentration of fumigant. For the high concentration exposure tests (3,000 ppmv target concentration), the GMP directly fed the test chamber to reach the desired target ClO_2 concentration within the shortest time. For the low concentration exposure tests (target concentration 75 ppm), a mixing chamber was used to feed the test chamber; the mixing chamber concentration was set to 3,000 ppmv

2.6 Fumigation Event Sequence

The impact of the ClO_2 exposure on materials and electronic equipment was investigated for different fumigation conditions and operational states of the equipment (ON/OFF). The testing approach consisted of first investigating the impact on Category 2 and 3 items, followed by completing the test matrix for the Category 4 items. Each fumigation event sequence can be generalized as follows:

Pre-conditioning Phase:
During this phase, both the test and the control MEC chambers were conditioned to maintain a constant, pre-determined temperature and RH.

Exposure Phase:
The exposure phase in the test chamber is divided into two sequences:

1) *Fumigant Charging Phase*. The fumigant charging phase corresponds to the time required ClO_2 concentration. The CT (ppmv-hours) of the charging phase was around one percent of the total CT accumulated in the overall exposure phase.

2) *Exposure Phase*: The exposure phase corresponds to the set concentration time exposure (CT). Time zero was set as the time when the MEC test chamber reached the desired concentration (±10 percent standard deviation). The required CT was set to 9,000 ppmv-hour for the high ClO_2 concentration (3,000 ppmv) and to 900 ppmv-hours for the low MEC test chamber concentration (75 ppmv).

Aeration phase:
The aeration phase started when the exposure phase was completed (i.e., when the target CT had been achieved), proceeded overnight, and stopped when the concentration inside the chamber was below the OSHA permissible

exposure limit (PEL) for chlorine dioxide of 0.1 ppmv (0.3 milligrams per cubic meter (mg/m^3)) as an eight-hour time-weighted average (TWA) concentration.

The phases of a fumigation event are graphically depicted in Figure 2-3. The times and demand rates for each phase shown are presented for illustration purposes only.

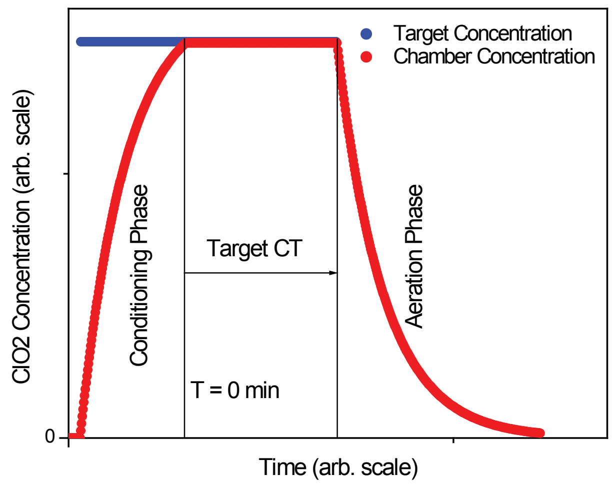


Figure 2-3. Material and Equipment Exposure Time Sequence.

3.0 Testing and Measurement Protocols

Testing to accomplish the test matrices used two isolation test chambers: the MEC control chamber for the control tests (no fumigant), and the MEC test chamber for the fumigant test conditions. The chambers were controlled to establish fumigation conditions that were identical with respect to temperature, RH, and air exchange rate. Tested materials and equipment were photographed before and after exposure and any visual changes noted, including color, legibility, and contrast. Off-gassing (i.e., noticeable odor) was also documented.

3.1 Methods

The photometric monitors (GMP monitor and EMS), the Interscan LD233 continuous ClO_2 gas monitor, and the extractive modified Standard Method 4500-ClO_2 E were used for monitoring ClO_2 concentrations in the MEC test chamber and source chamber (GMP Box, as needed for the low concentration tests). Table 2-2 specifies where these methods were used within the experimental setups.

In addition to ClO_2 measurements, other critical parameters measured were temperature and RH. The Vaisala T/RH sensor used for control was compared against a Vaisala T/RH sensor used as a reference (never exposed to fumigant) before each test (see Section 3.1.4). Secondary measurements in different locations within the chamber were measured by HOBO® U10 data loggers, and also compared to the standard meter.

BIs were also included in the testing of Category 4 equipment. The use of the BIs provided an indication of whether or not acceptable decontamination conditions were achieved due to variations in local conditions within the computers.

The measurement equipment used in this project is described below.

3.1.1 Photometric Monitors

The ClorDiSys EMS monitor is identical to the photometric monitor built into the ClorDiSys generator (GMP), which was used to generate the ClO_2 in this study. Comparisons of the two instruments performed in a separate study indicated the two instruments read within 3 percent of one another with an R^2 value of 0.99.[16]

The monitors are photometric systems operating in absorbance mode with a fixed path cell. An internal pump in the EMS and GMP provides flow of the test gas from the sample point to the analytical cell. The maxima and minima of an unspecified and proprietary ClO_2-specific absorbance band are monitored. These numbers are then used to calculate the absorbance at this analytical band. Before delivery, calibration was performed with National Institute for Standards and Technology (NIST)-traceable transmission band pass optical filters (385/0.9CU; optek-Danulat, Inc., Essen, Germany). The photometric systems include a photometer zero function to correct for detector aging and accumulated dirt on the lenses. Daily operation of the photometers includes moments when clean, ClO_2-free air is being cycled through the photometers. If the photometer reads above 0.1 milligrams per liter (mg/L) during these zero air purges, then the photometer is re-zeroed. Problems arising from condensation when sampling under high temperature or high RH conditions have been addressed by heating the sample lines and the photometer cell. Table 3-1[17, 18] provides instrument specifications.

Table 3-1. CSI EMS/GMPs Photometric Monitor Characteristics

Parameter	Value	
	mg/L	ppm
Precision (SD[1])	0.1	36
Range	0.1-30	50-10,900
Accuracy (SD)	0.2 from 0.5-50	72 from 181-18,100
Resolution	0.1	36

[1] SD stands for Standard Deviation

3.1.2 Modified Standard Method 4500-ClO_2 E

Standard Method 4500-ClO_2 E is an amperometric titration suitable for aqueous ClO_2 concentrations between 0.1 to 100 mg/L. This method does not address gas-phase sampling. The full method is quite complex in that a multi-titration scheme is used to differentiate several chlorine-containing analytes. A modification of this method to incorporate gas-phase sampling is to use a buffered potassium iodide bubbler sample collection and restrict the official method to a single titration based upon Procedure Step 4.b.[19] This step analyzes the combined chlorine, chlorine dioxide, and chlorite as a single value, and can only be applied where chlorine and chlorite are not present. Since the modified method (modified Standard Method 4500-ClO_2 E) described below is applied to gas-phase samples, the presumption of the absence of chlorite and chlorate is quite valid. The presumption of the absence of chlorine is based upon experience by multiple generator manufacturers and research groups, along with preliminary tests performed previously.[16]

A discussion of the modified method Standard Method 4500-ClO_2 E used in this test plan can be found in the approved QAPP entitled, "Fumigant Permeability and Breakthrough Curves, Revision 1, April 2006."[16] The modified Standard Method 4500-ClO_2 E is performed as follows:

- Add 20 mL of phosphate buffer solution, pH 7.2 with KI (25 g KI/ 500 mL of buffer phosphate) (KIPB solution) to two impingers.
- Route ClO_2 gas from the chamber into the KIPB solution in the impingers in series at a flow rate of 0.5 L/min for four minutes.
- Combine the 20 mL of KIPB solution from each impinger into a 200 mL volumetric flask and rinse the impingers thoroughly with de-ionized water. Fill the flask to the 200 mL mark.
- Dilute 5 mL of the resulting solution to 200 mL with deionized water and add 1 mL of 6 N HCl to the solution.
- Place solution in dark for five minutes.
- Titrate the solution with 0.l N sodium thiosulfate (N = 0.1).
- Record the volume of sodium thiosulfate used in the titration. Conversion calculations from titrant volume to ClO_2 concentration are based on Standard Method 4500-ClO_2 E
- ClO_2 (mg/L) = Volume of sodium thiosulfate (mL) x N x 13490 /0.025 (fraction of gas titrated)

Where N = Normality.

This method removes many of the possible interferences listed in Standard Method 4500-ClO_2 E.[19] The initial presence of KI in excess prevents iodate formation, which can occur in the absence of KI and leads to a negative bias. The presence of the pH 7 buffer during impinging prevents oxidation of iodide by oxygen which occurs in strongly acidic solutions. Other interferences are unlikely to be a problem in this application, as the presence of manganese, copper, and nitrate is unlikely in a gaseous sample.

The second impinger filled with buffered KI solution is added in series to reduce the likelihood of breakthrough. The second impinger was not analyzed independently, but was combined with the first impinger for analysis. System blanks were done, on a daily basis, by titration of the KIPB sample. When titration yielded a volume of titrant greater than 0.5 percent of the expected value of the impinged sample, a new KIPB solution was mixed to provide a lower blank value.

3.1.3 Interscan LD233

The Interscan LD233 is an electrochemical voltametric continuous monitoring system similar in theory to the operation of the Dräger sensors that are being used in concurrent NHSRC studies in DTRL. The Interscan LD233 is essentially two separate analyzers in one, measuring ClO_2 in two ranges, 0-1999 ppb and 0-19.99 ppm. The resolution and detection limits are listed in Table 3-2. This instrument may be used in parallel with the Dräger in order to add additional verification of the low concentration. To measure the 75 ppm range with the Interscan LD233, a 10:1 dilution system must be used. This dilution was done directly from the MEC test chamber in the sampling scheme.

Table 3-2. Interscan LD233 Specifications

Range	0-1999 ppb	0-19.99 ppm
Resolution	1 ppb	0.01 ppm
Minimum Detection	20 ppb	0.2 ppm

3.1.4 Temperature and RH Measurement

Temperature and RH measurements were performed with two types of sensors, the Vaisala HMP50 transmitter and the HOBO® U10 logger. The Vaisala transmitter was used for the real-time control of humidity, and was placed at a point distant from the steam injector. The HOBO® loggers were put in various places within the MEC test and control chambers and within computers (Category 4), to provide a map of humidity and temperature conditions. The specifications of both instruments are shown in Table 3-3.

Table 3-3. RH and Temperature Sensor Specifications

Instrument	Vaisala	HOBO®
RH Range	0 to 98%	25 to 95%
RH Accuracy – 0 to 90%	± 3%	± 3.5%
RH Accuracy – 90 to 98%	± 5%	Unknown
RH Resolution	0.001% [1]	0.07%
Temperature Range	-10 to 60 °C	-20 to 70 °C
Temperature Accuracy	± 0.6 °C @ 20 °C	± 0.4 °C @ 25 °C
Temperature Resolution	0.001 °C [1]	0.1 °C

[1] Vaisala resolution estimated from 22-bit resolution of personal data acquisition system (PDAQ).

Repeated exposure to fumigation conditions degrades both instruments. In the case of the Vaisala, the RH sensor becomes corroded and the higher resistance results in inaccurate RH readings. Corroded sensors were detected and replaced during the RH sensor comparisons before each test (see below). In the case of the HOBO®, the fumigant corrodes the circuit board so that download of the logged data is sometimes impossible. To help prevent this reaction, the HOBO® circuit board was coated in a watertight sealant, taking care not to coat the sensor elements themselves. This coating did not affect the reading of the HOBO® and allowed the instrument to survive the fumigation in most cases.

A separate, calibrated Vaisala HMP50, never exposed to fumigation, was used as an independent reference. Before each test, each sensor was compared to the reference sensor at ambient (~40 percent RH) and at 75 percent RH. If the Vaisala differed from the reference by more than 4 percent, then the removable RH sensors were replaced (independent of the rest of the transmitter). The RH measurements from the HOBO® sensors are used only for qualitative comparisons with the Vaisala sensor.

3.1.5 Biological Indicators (BIs)

The BIs for this effort were acquired from Apex Labs (Sanford, NC). The BIs as received were *Bacillus atrophaeus (B. atrophaeus)* spores, nominally $1x10^6$, on stainless steel disks in Dupont™ Tyvek® envelopes. These BIs have been used extensively in NHSRC-related fumigation efficacy testing for *B. anthracis* spores deposited onto building materials. While it is easier to inactivate the spores on the BIs than on most materials, BIs can provide a suitable indication of failure of the inactivation of *B. anthracis* on surfaces. Thus, failure to inactivate the BIs suggests that conditions required to inactivate spores on environmental surfaces were not achieved.[20] Further, the inactivation of *B. anthracis* spores on building materials and *B. atrophaeus* spores on the stainless steel BIs is highly sensitive to RH. For inactivation with ClO_2, spores require a minimum of 65 - 75 percent RH for effective kill conditions.[2]

Within operational computers, higher local temperatures were expected to be associated with lower RH than the bulk of the chamber. Therefore, BIs were placed in the bulk chamber and within each computer in order to assess a difference in the failure to achieve the appropriate decontamination conditions. Five BIs were collocated in each computer and in the MEC test and control chambers. After removal from the chambers and computers after testing, the BIs were transferred to the Air Pollution Prevention and Control Division's (APPCD's) Microbiology Laboratory. The transfer was accompanied by a chain of custody (COC) form for each group of five BIs. In the Microbiology Laboratory, the BIs were transferred aseptically from their envelopes to a sterile conical tube (Fisherbrand, Thermo Fisher Scientific, Inc., Waltham, MA) containing at least 25 mL of nutrient broth (NB) (BBL Dehydrated Nutrient Broth, BD Diagnostics Systems, East Rutherford, NJ). Each BI was placed in an individual sample tube; both positive and negative controls were analyzed in conjunction with each test group for quality assurance. The tubes were incubated at 23 °C for seven days, and then recorded as either "growth" or "no growth" based upon visual inspection. Tubes with growth turned the NB very cloudy and consistency of the NB was changed. All tubes were plated on tryptic soy agar (TSA) (Remel Inc., Lenexa, KS) to confirm that any growth in the tube was indeed *B. atrophaeus* and not another organism that had contaminated the samples. Using aseptic techniques, the TSA plates were incubated overnight at 32 °C. A visual inspection of the plates was performed the following day to determine if the *B. atrophaeus* had grown; *B. atrophaeus* grows producing a reddish tint on the agar. Both positive and negative controls were used to confirm that *B. atrophaeus* growth on TSA was consistent.

3.1.6 Visual Inspection

Visual inspection focused on the expected effects of fumigation: a change in color and occurrence of corrosion. The color change could also affect legibility of printed paper materials. Digital photographs of each coupon or material were taken prior to fumigation. After fumigation, digital photographs were taken to document the condition of the materials/equipment. Some equipment was partially dismantled in order to take digital photographs of the equipment inside the casing. This dismantling was done at an approved electrostatic discharge (ESD) station (Section 3.4). Any changes in legibility or contrast of materials before/after fumigation were recorded.

3.1.7 Functionality Testing

All electronic equipment in Category 3 and 4 underwent functionality testing prior to and after fumigation, as did selected materials from Category 2, as appropriate. These tests were detailed in Tables 1-1 and 1-3 for the Category 2 and 3 materials, respectively.

For the Category 4 equipment, the protocols for the computer setup and analysis were developed by Alcatel-Lucent for the specific equipment included in this category (see Appendix D of the EPA QAPP entitled, "Compatibility of Material and Electronic Equipment with Chlorine Dioxide Fumigation," dated July 2007). After exposure to the test conditions, all Category 2 and 3 materials were maintained in an RH- and temperature-controlled room for one year for follow-up testing. Category 4 equipment was tested in triplicate; after the post-fumigation functionality test, one of the three Category 4 computers was sent to Alcatel Lucent for in-depth failure analysis; the remaining two computers per test run remained at DTRL for continued functionality testing for one year. The post-fumigation analysis continued monthly for these pieces of Category 4 equipment (except for months 9 and 11), and for the first five months and then again at the one-year point for all Category 2 and 3 materials. Based on observations of effects, the post-fumigation testing schedule was modified to reduce the number of evaluations in a way that did not compromise achieving the overall objectives of this project. During the one year period, all equipment was stored in an indoor office/laboratory environment with logged temperature and RH. The computer systems were maintained in the operational (ON) state and were put through a BIT sequence five days a week, for eight hours a day, to simulate normal working conditions. Functionality testing was done by running a predefined routine specific to each of the items. These routines were documented for each item and maintained in the item's log book or test sheets, which were then taped into the logbook. For the computer systems, PC-Doctor® Service Center™ 6 was run to complete a hardware and software diagnostic investigation. The BIT sequence and PC-Doctor® Service Center™ protocols were developed by Alcatel-Lucent specifically for this testing. The results of the diagnostic protocol were maintained in the appropriate log book.

3.1.8 Detailed Functionality Analysis (subset of Category 4)

The assessment of the impact of fumigation on Category 4 equipment was performed in conjunction with Alcatel-Lucent through LGS Innovations, Inc. as the prime performer of a CBRTA IA&E. One computer and monitor from each of the seven test sets was sent to Alcatel-Lucent for detailed functionality testing. The worst-performing computer from each of the triplicate test sets was chosen for this in-depth testing. These computers and monitors, after undergoing the initial pre-/post-fumigation visual (Section 3.1.7) and functionality screening (Section 3.1.8), were preserved and shipped according to Section 3.4. The computers were shipped to Alcatel-Lucent without forwarding knowledge of the conditions under which the equipment was treated (i.e., test information was not provided). Alcatel-Lucent used a hierarchical approach to the analysis. The order or increasing level of analysis was (1) aesthetic and functionality evaluation (energize, run diagnostic protocol), (2) visual inspection and more advanced diagnostics to identify affected components, (3) modular investigation, and (4) cross-section and failure mode analysis. The metal coupons and IPC boards were also analyzed by Alcatel-Lucent for visual impacts and changes in conductivity (i.e., IPC boards).

3.2 Cross-Contamination

The two isolation chambers, MEC test and control, were set up in two different laboratories. There was no contact between the two chambers in order to eliminate any potential exposure of the MEC control chamber to the fumigant because the reuse of limited PC-Doctor® Service Center™ 6 hardware between computers has raised the possibility of cross-contamination by the transfer of corrosion products.[15]

3.3 Representative Sample

Materials and equipment were chosen as representative of, or as surrogates for, typical indoor construction materials or modern electronic devices. Each material or piece of equipment was tested in triplicate for representativeness. After initial inspection to confirm the representativeness of the Category 4 equipment post-treatment under the test conditions, the set that fared the worst from each test condition was sent for the detailed analysis performed by Alcatel-Lucent. The initial inspection was an assessment for visual changes and PC diagnostic using PC-Doctor® Service Center™ 6.[21]

3.4 Sample Preservation Methods

Test samples (i.e., materials and equipment) were stored in temperature- and RH-controlled, indoor ambient laboratory conditions until testing was performed. All samples, both test and control, were stored under the same conditions prior to and after the fumigation event.

The Category 4 items, specifically the computers and monitors, were treated differently from the items included in the other categories. Due to the detailed analysis a subset of this test equipment was to undergo, this equipment was stored in the original shipping packaging until anti-static and anti-corrosion bags (Corrosion Intercept Technology; http://www.staticintercept.com/index.htm) could be obtained. These bags were developed by Bell Laboratories and recommended by Alcatel-Lucent. The bags are specifically designed to protect the bagged equipment from exposure to potentially damaging electrostatic charge or corrosive gases. The computers and monitors were removed from their original packaging, labeled with a designated sample number (see Section 3.5), and set up according to the protocol provided by Alcatel-Lucent. After the pre-test analysis, the computers were dismantled, placed in an individual bag, sealed and stored until reassembly and preparation for the fumigation event. The computers were also dismantled and bagged during transport to and from the MEC chambers. After exposure to the test conditions, the equipment underwent visual inspection and initial diagnostics with PC-Doctor® Service Center™ 6. The protocols for running PC-Doctor® Service Center™ 6 were developed and provided by Alcatel-Lucent, pecifically for the equipment included in this testing. One computer and monitor from each test group was transferred back to its respective bag and stored until the completion of the test matrix for Category 4. Once completed, the bagged equipment was shipped to Alcatel-Lucent for the detailed analysis. The Category 4 items not shipped and all Category 2 and 3 items were transferred to an appropriate area (ESD work station, E-288, see below) in which the computers and monitors could remain energized and operated over the course of a year to continually assess delayed effects due to the test conditions under which they were treated. The temperature and RH in the area were monitored and logged.

Before testing of the computers, the systems were opened to insert a T/RH monitor (HOBO® U10) and BIs in each desktop case. The Category 4 metal coupons and IPC board were also placed in each computer case. The location and method of fastening the equipment inside the case were specified by Alcatel-Lucent. The insides of the desktop computers were digitally photographed. To maintain the integrity of the computer by avoiding static electricity, an electrostatic discharge work station (ESD Station) was established for work on the computers. An ESD station was set up in E-288 (EPA Facility, RTP, NC) and a second sub-station (smaller) next to the MEC test chamber in H-224 (EPA Facility, RTP, NC). Training on this work station in E-288 was provided by Alcatel-Lucent on July 18, 2007. In general, the station consisted of an electrostatic discharge work mat, an electrostatic monitor, and electrostatic discharge wrist bands. All computers were inspected and operated (i.e., diagnostic testing, long-term operation of computers for analysis of residual effects) on the certified ESD work stations according to certified procedures. During operation of the computers, all computers were energized using surge protectors (BELKIN seven-outlet home/office surge protector with six-foot cord, Part # BE107200-06) (Belkin International, Inc.; Compton, CA).

The *B. atrophaeus* BIs were maintained in their sterile Dupont™ Tyvek® envelopes, refrigerated, until ready for use. The BIs were allowed to come to the test temperature before being placed in the MEC test chamber. The BIs were maintained in their protective Dupont™ Tyvek® envelopes until transferred to the on-site Microbiology Laboratory for analysis.

Modified Method 4500E samples were kept in a dark refrigerator for one week after initial analysis for potential re-titration.

3.5 Material/Equipment Identification

Each material and piece of equipment was given an identifying code number unique to that test sample material/equipment. The codes and code sequence were explained to the laboratory personnel to prevent sample mislabeling. Proper application of the code simplified sample tracking throughout the collection, handling, analysis, and reporting processes. All COC documentation for the test sample material/equipment was labeled with the identifying code number. Table 3-4 shows the sample coding used in this study, with Figures 3-1 through 3-9 showing pictures of all of the materials that were tested. The Category 4 equipment was labeled as DECON###, where ### refers to a three-digit sequential number. A total of 24 computers and liquid crystal display (LCD) monitors were purchased for this project; therefore, the numbers ranged from 001 to 024. Of these 24 computers, DECON001 was not tested. Sample DECON001 served as a control sample. The experimental log for the tests cross-referenced the label on the computer equipment (i.e., DECON001) to the coding shown below with respect to Category 4. The use of the generic labeling for Category 4 equipment was required to maintain a blindness of the analysis for the equipment sent to Alcatel-Lucent. The cross-reference between the generic label (DECONXXX) and the coding shown below was not provided to Alcatel-Lucent.

Table 3-4. Sample Coding

AAA-NN-TXX-RXX			
	Sample Code	**Figure**	**Sample Type**
AAA	2AL	3-1a	3003 Aluminum coupons
	2CU	3-1b	101 Copper coupons
	2CS	3-1c	Low carbon steel coupons
	2S1	3-1d	410 Stainless steel coupons
	2S3	3-1e	430 Stainless steel coupons
	2S4	3-1f	304 Stainless steel coupons
	2S6	3-1g	316 Stainless steel coupons
	2S9	3-1h	309 Stainless steel coupons
	2SW	3-2a	Stranded wires
	2LC	3-2b	DSL conditioner
	2EB	3-2c	Steel outlet/Switch box
	2SE	3-2d	Sealants (caulk)
	2GA	3-2e	Gaskets
	2DS	3-2f	Drywall screw
	2DN	3-2g	Drywall nail
	2CS*	3-3a,b,c	Copper services
	2AS	3-3d,e,f	Aluminum services
	2CB	3-3g	Circuit breaker
	2SD	3-4a	Smoke detector
	2SW**	3-4b,c	Switches (lamps)
	2LP	3-5a	Laser printed colored papers (stack of 15 pages)
	2IP	3-5b	Ink jet printed colored papers (stack of 15 pages)
	2PH	3-5c	Photographs
	3PD	3-6a	PDAs
	3CE	3-6b	Cell phones
	3FA	3-6c	Fax machines (with telephones)
	3DV	3-7a	DVDs
	3CD	3-7b	CDs
	4CO	3-8a	Desktop computer
	4MO	3-8a	Computer monitor
	4KB	3-8b	Computer keyboard
	4PC	3-8c	Computer power cord
	4CM	3-8d	Computer mouse
	BIX	3-9	Biological Indicator (X=1 for inside Computer 1, X=2 for inside Computer 2, X=3 for inside Computer 3, X=4 for inside bulk chamber)
NN	01, 02, or 03		Replicate number (01, 02, 03)
TXX	T01 or T02		Test Matrix (Category 2 and 3 = T01; Category 4 = T02)
RXX	R01 – R08		Run Number (R01-R08)

* 2CS was used for low carbon steel coupons and the copper services.
** 2SW was used for stranded wire and the switches; also 2HW was deleted as a separate category (Housing wiring insulations) because 2HW was on the outside of the three-piece stranded wire (2SW).

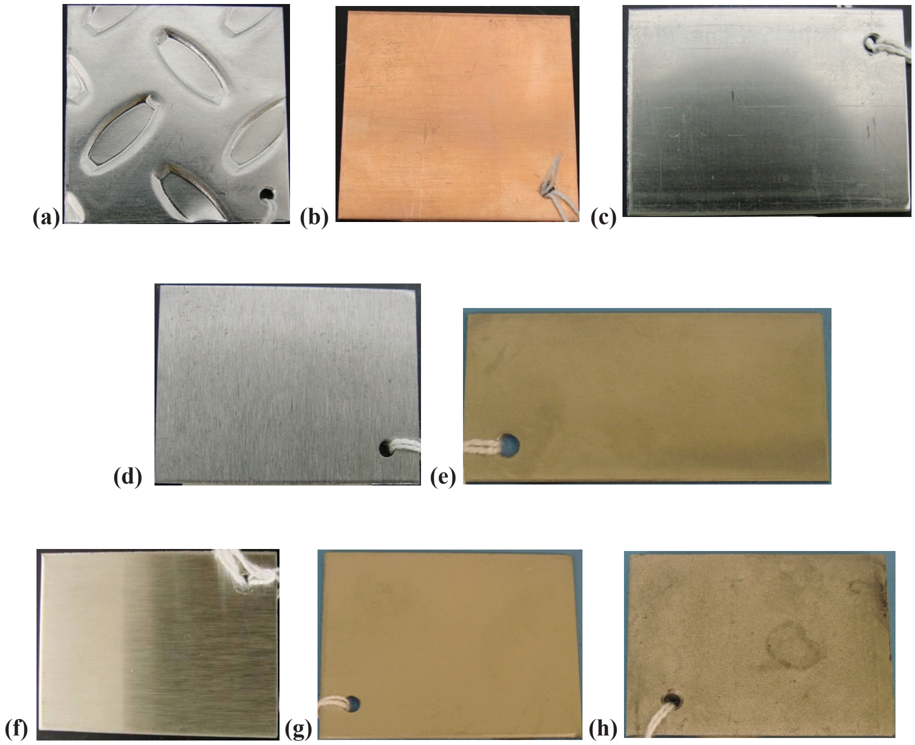


Figure 3-1. Metal Coupons used in the Compatibility Testing (photos prior to fumigation):
(a) 3003 Aluminum; (b) 101 Copper; (c) Low Carbon Steel; (d) 410 Stainless Steel; (e) 430 Stainless Steel; (f) 304 Stainless Steel; (g) 316 Stainless Steel; and (h) 309 Stainless Steel.

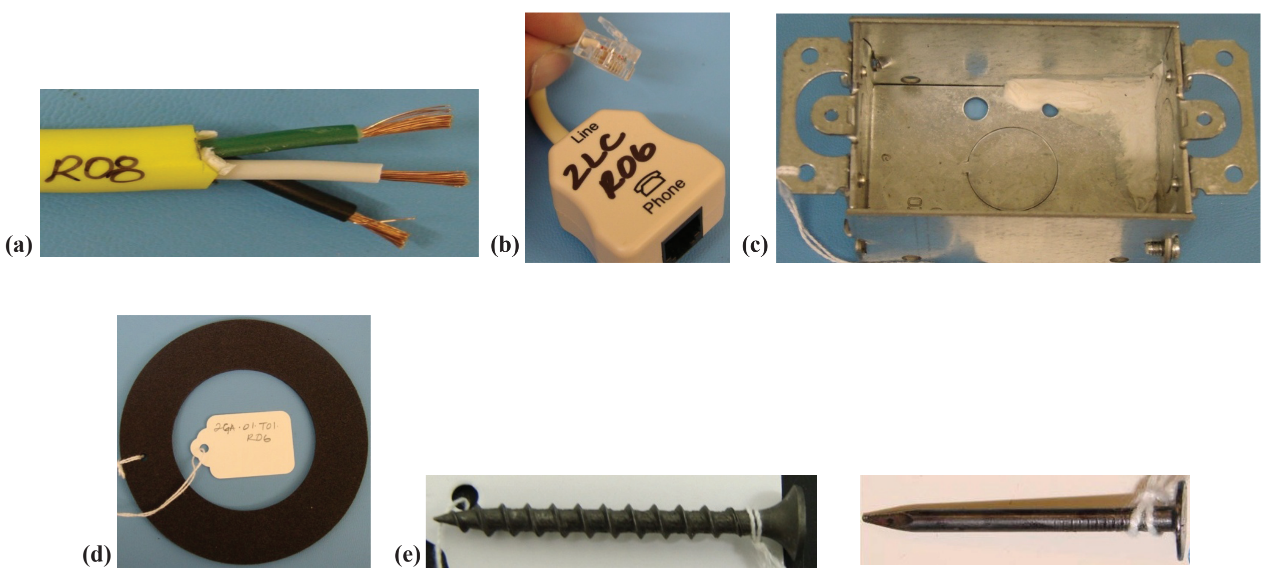


Figure 3-2. (a) Stranded Wire (b) DSL Conditioner (c) Steel Outlet/Switch Box with Sealant (Caulk) (d) Gasket (e) and Drywall Screws and Nails used in the Compatibility Testing.

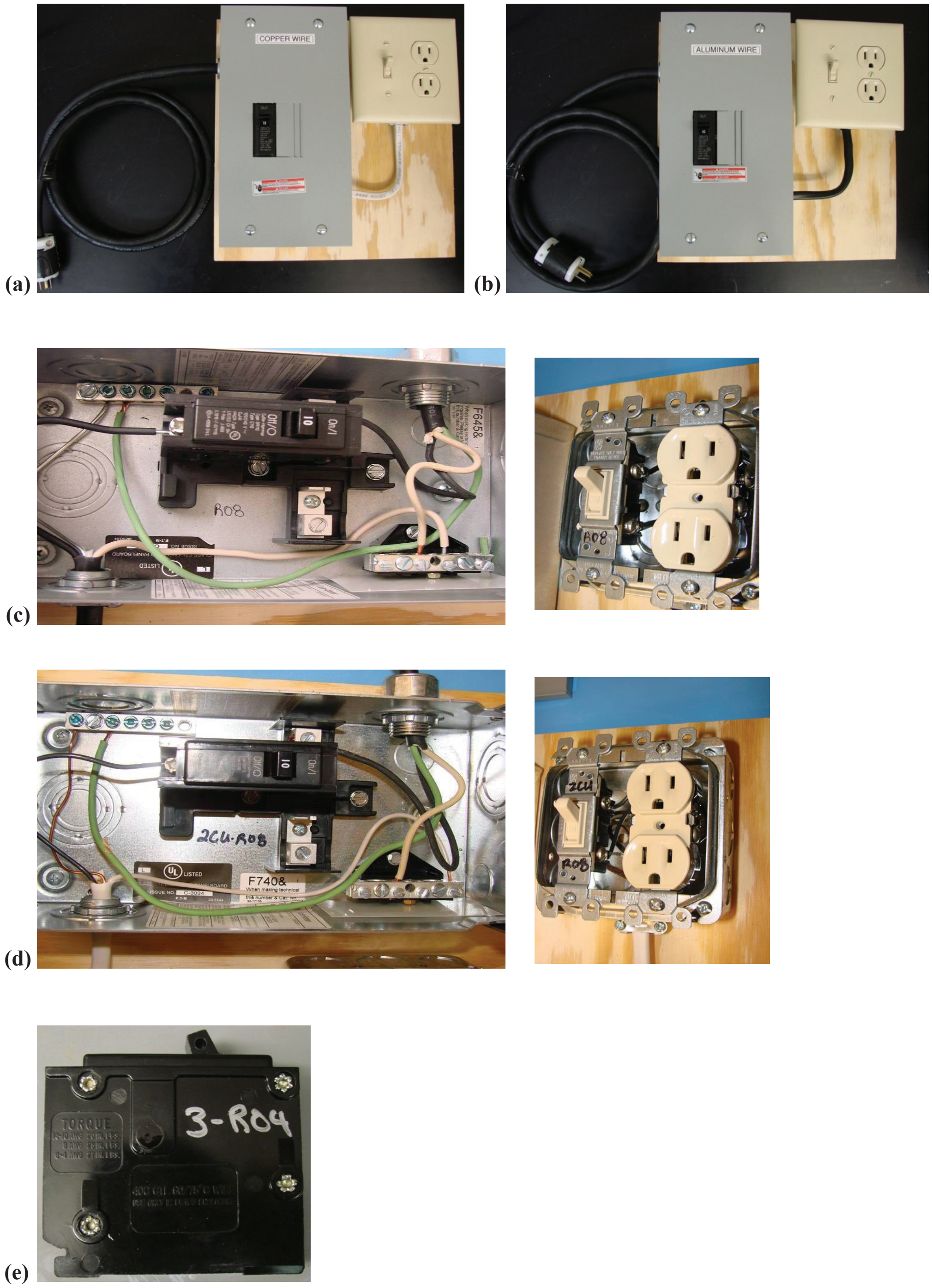


Figure 3-3. (a, c) Copper Services, (b, d) Aluminum Services, and (e) Circuit Breaker used in the Compatibility Testing.

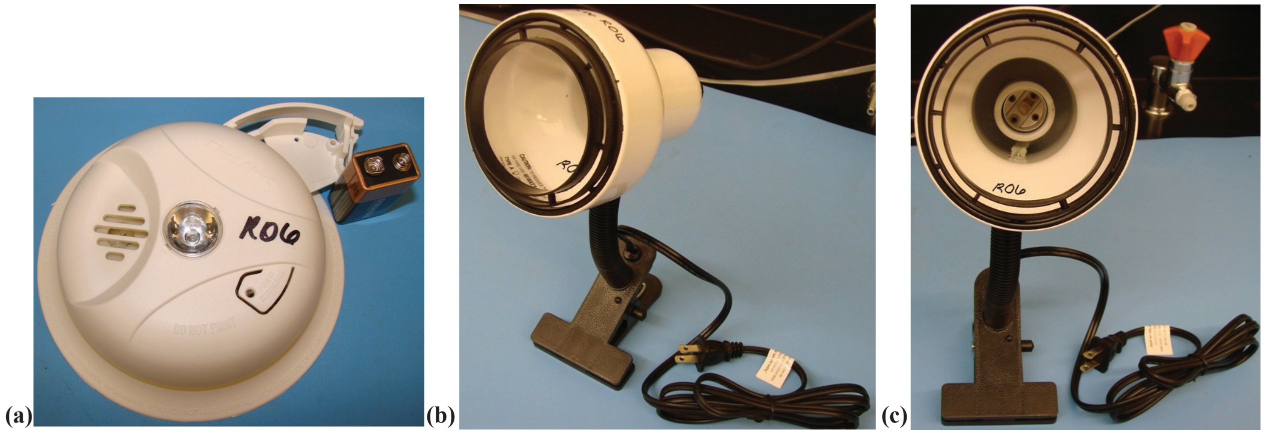


Figure 3-4. (a) Smoke Detector and (b, c) Lamp Switch used in the Compatibility Testing.

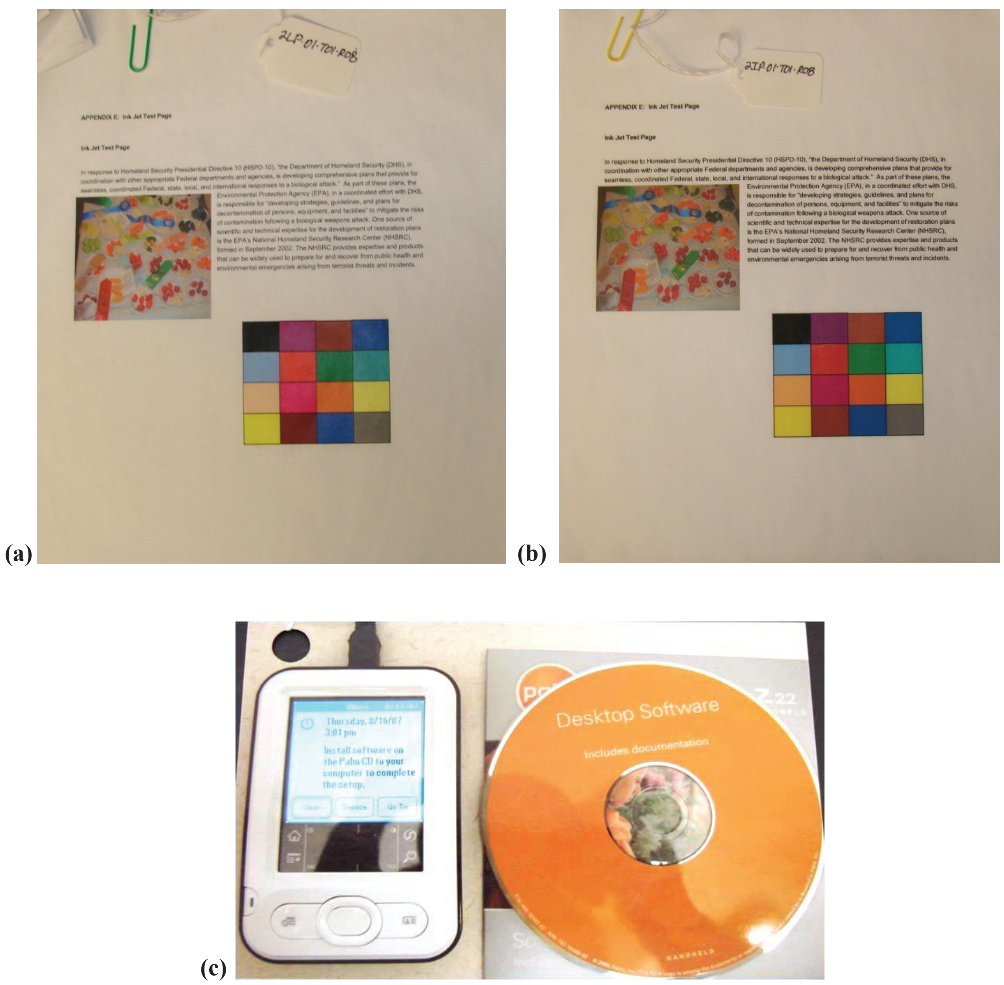


Figure 3-5. (a) Laser and (b) Inkjet Printed Color Papers, and (c) Photograph used in the Compatibility Testing.

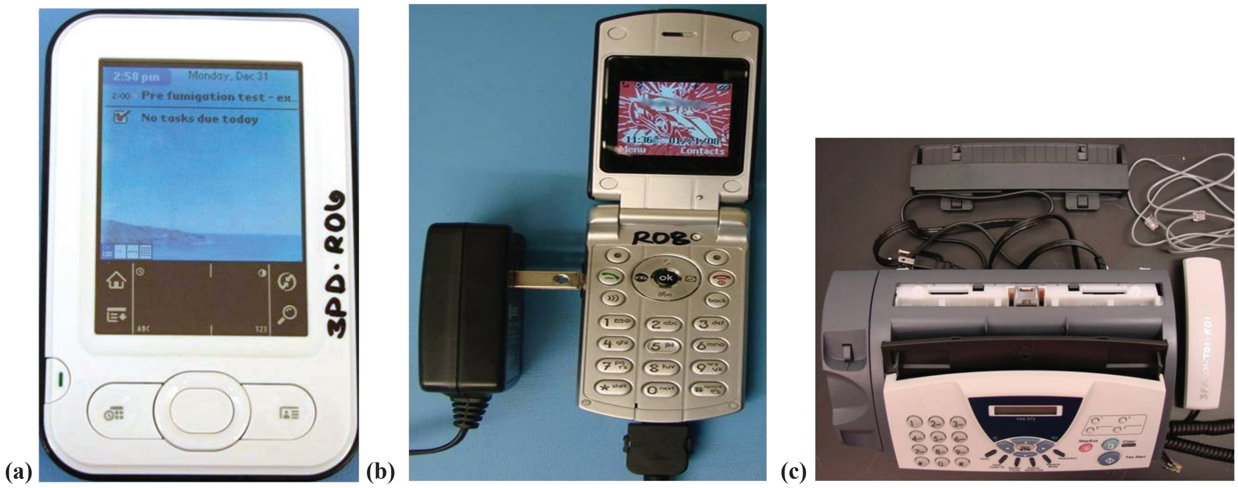


Figure 3-6. (a) PDA (b) Cell Phone, and (c) Fax Machine used in the Compatibility Testing.

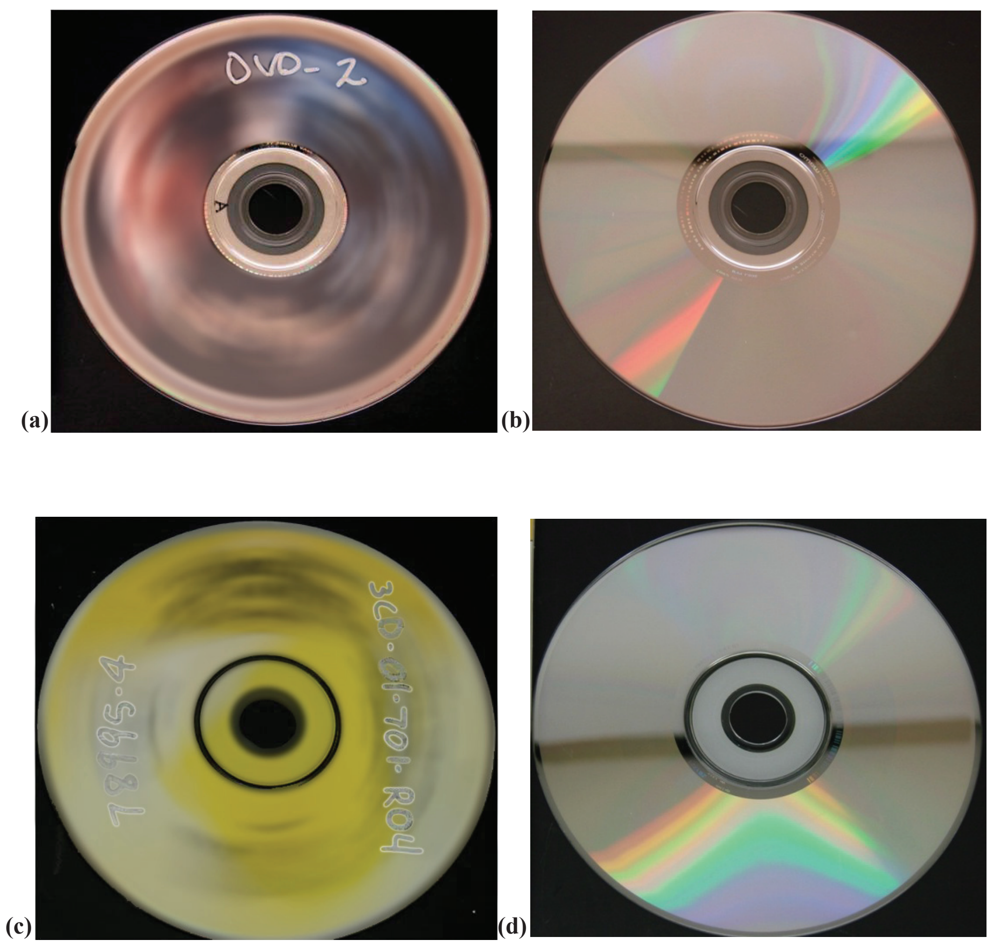


Figure 3-7. (a) Front of DVD (b) back of DVD (c) front of CD, and (d) back of CD used in the Compatibility Testing.

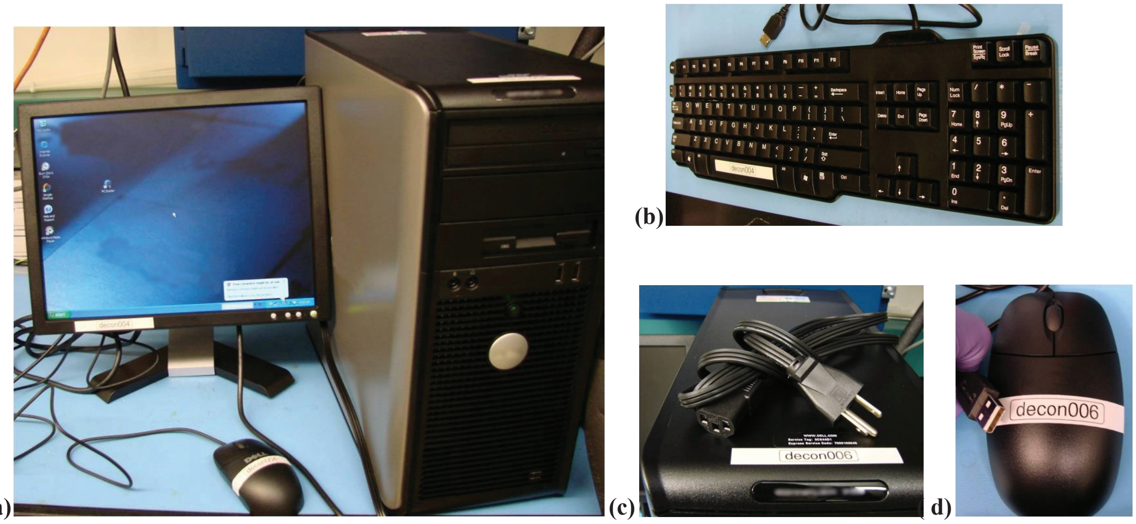


Figure 3-8. (a) Desktop Computer and Monitor, (b) Keyboard, (c) Power Cord, and (d) Mouse used in the Compatibility Testing.

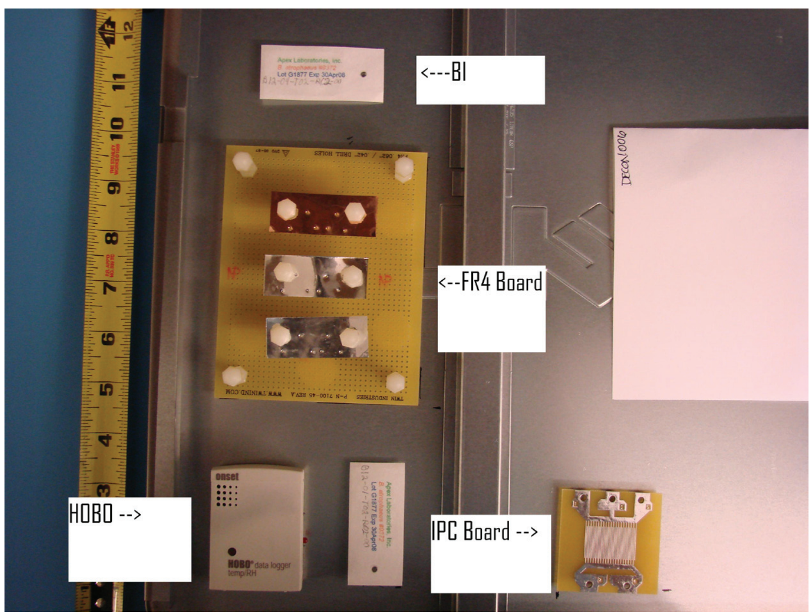


Figure 3-9. Inside of a Computer Showing Two of the Five BIs, the HOBO® Data Logger, the IPC Board, and the Mounted Metal Coupons.

3.6 Sample Shipping Procedures

The computer, monitor, and ancillary equipment shipped to Alcatel-Lucent were packaged inside Corrosion Intercept Technology bags (http://www.staticintercept.com/index.htm). The bagged equipment was shipped to Alcatel-Lucent using the original packaging (i.e., boxes and foam) after post-fumigation tests. The shipping and handling protocols were provided by Alcatel-Lucent.

3.7 Chain of Custody

Each material/piece of equipment sent to Alcatel-Lucent had a COC record describing the material/equipment and analysis to be performed. Similarly, all the BI samples sent for analysis by the On-site Microbiology Laboratory had a COC. Examples of the COC forms for the transfer of the BI samples to the Microbiology Laboratory and the Category 4 equipment to Alcatel-Lucent are provided in Appendix B of the EPA QAPP entitled, “Compatibility of Material and Electronic Equipment with Chlorine Dioxide Fumigation,” dated July 2007.[22]

3.8 Test Conditions

Two sets of test conditions were used for the testing. Test condition T01 was used for Category 2 and 3 materials (combined) and test condition T02 was used for Category 4 equipment. The test conditions were based on the main objective of this project: to assess the damages, if any, to materials and electronic equipment functionality after remediation of a contaminated space using the ClO_2 technology under various fumigation scenarios and equipment states of operation. The parameters that were investigated include:

1. Effect of fumigation at high concentration (3,000 ppmv ClO_2) at standard conditions (75 percent RH, 24 °C) with a CT of 9,000 ppmv-hr;
2. Effect of fumigation at low concentration (75 ppmv ClO_2) at standard conditions (75 percent RH, 24 °C) with a CT of 900 ppmv-hr;
3. Impact of the power state (ON/OFF) of the electronic equipment during the fumigation under the standard conditions (3,000 ppmv ClO_2, 9,000 ppmv-hr, 75 percent RH, 24 °C);
4. Impact on the equipment of standard (75 percent) and high (90 percent) RH during fumigation at high concentration (3,000 ppmv ClO_2, 9,000 ppmv-hr);
5. Impact on the equipment of the low (40 percent) RH during fumigation at low concentration (75 ppmv ClO_2, 900 ppmv-hr);
6. Impact of a high RH (90 percent) environment alone (without added ClO_2);
7. Impact of ambient conditions (40 percent RH) only.; and
8. Impact of fumigation time (or CT) and duration of use after a fumigation event.

The test conditions for Category 2 and 3 materials are presented in Table 3-5 and for Category 4 equipment in Table 3-6. Tests without ClO_2 added were performed in the MEC control chamber; all other tests were performed in the MEC test chamber.

Table 3-5. Test Conditions for Category 2 and 3 Materials

Test Condition	Run Name	Treatment Conditions and Equipment Power State	Purpose of Test
1	**R01**	*Standard Fumigation:* 3,000 ppmv ClO_2 75% RH 24 °C 3 hours ON	Determine the effect of standard fumigation conditions.
2	**R02**	*High RH Fumigation:* 3,000 ppmv ClO_2 90% RH 24 °C 3 hours ON	Determine the effect of standard fumigation concentration at higher RH and standard temperature. *Problem: Aborted due to condensation*
3	**R03**	*Low Concentration Fumigation:* 75 ppmv ClO_2 75% RH 24 °C 12 hours ON	Determine the effect of lower fumigation concentration at standard temperature and RH.
4	**R04**	*Low RH Fumigation:* 75 ppmv ClO_2 40% RH 24 °C 12 hours ON	Determine the effect of lower fumigation concentration at lower RH (ambient RH) and standard temperature.
5	**R05**	*Ambient Conditions Only, No ClO_2:* 0 ppmv ClO_2 40% RH 24 °C 12 hours ON	Determine baseline conditions. Determine the effect of no fumigation, lower RH, and standard temperature.
2	**R06**	*High RH Fumigation:* 3,000 ppmv ClO_2 90% RH 24 °C 3 hours ON	Determine the effect of standard fumigation concentration at higher RH and standard temperature. 1st rerun of Test Condition 2 (same conditions) *Problem: Condensation still present*
2	**R07**	*High RH Fumigation:* 3,000 ppmv ClO_2 88% RH 27 °C 3 hours ON	Determine the effect of standard fumigation concentration at higher RH and standard temperature. 2nd rerun of Test Condition 2 (raised the temperature 5 °F and lowered RH 2%) *Problem: Condensation still present*
6	**R08**	*High RH, No ClO_2:* 0 ppmv ClO_2 90% RH 24 °C 3 hours ON	Determine baseline conditions for run for Test Condition 2 (since condensation could not be avoided at higher RH). Determine the effect of no fumigation, higher RH, and standard temperature (isolate effect of combination of ClO_2 and higher humidity).

Table 3-6. Test Conditions for Category 4 Equipment

Test Condition or Run Name	Subset Run Name or Computer Label	Treatment Conditions and Equipment Power State	Purpose of Test
1	DECON004 **DECON006** DECON014	Standard Fumigation: 3,000 ppmv ClO_2 75% RH 24 °C 3 hours OFF	Determine the effect of standard fumigation conditions with power OFF.
2	DECON003 **DECON012** DECON023	Standard Fumigation: 3,000 ppmv ClO_2 75% RH 24 °C 3 hours ON	Determine the effect of standard fumigation conditions with power ON.
3	**DECON011** DECON016 DECON024	High RH Fumigation: 3,000 ppmv ClO_2 90% RH 24 °C 3 hours ON[1]	Determine the effect of standard fumigation concentration at higher RH and standard temperature.
4	DECON009 **DECON010** DECON021	High RH, No ClO_2: 0 ppmv ClO_2 90% RH 24 °C 3 hours ON[1]	Determine the effect of no fumigation, higher RH, and standard temperature (isolate effect of combination of ClO_2 and higher humidity).
5	**DECON002** DECON008 DECON019 DECON013[2] DECON017[2] DECON020[2]	Low Concentration Fumigation: 75 ppmv ClO_2 75% RH 24 °C 12 hours ON[1]	Determine the effect of lower fumigation concentration at standard temperature and RH.
6	DECON005 DECON007 **DECON022**	Low RH Fumigation: 75 ppmv ClO_2 40% RH 24 °C 12 hours ON[1]	Determine the effect of lower fumigation concentration at lower RH (ambient RH) and standard temperature.
7	**DECON015** DECON018	Ambient Conditions Only, No ClO_2: 0 ppmv ClO_2 40% RH 24 °C 12 hours ON[1]	Determine baseline conditions. Determine the effect of no fumigation, lower RH, and standard temperature.

Note: **Bold** indicates computer systems sent to Alcatel-Lucent for detailed IA&E.

[1]The power states for Test Sets 3 through7 were determined based on the impact determined in Test Sets 1 and 2.

[2]Condensation occurred in these computers due to a faulty valve; therefore, the computers were not used in the testing.

4.0 Visual Inspection

Photographs were to be taken as part of the scheduled functionality testing.

The purpose of this physical documentation was to make comparisons over time, looking for changes such as discoloration of wire insulation, corrosion, residue, and decrease in the quality or readability of documents and photographs. Where changes were noted, all visual files and written documentation were reviewed to provide a detailed understanding of the effects of fumigation over time on that material/component. Functional effects are presented and discussed in Section 5.

4.1 Category 2 Materials

A description of the visual changes documented in Category 2 materials is detailed in Table 4-1. A summary of the noted visual changes by run number (condition) is shown in Table 4-2. Impacts were observed primarily in the high RH runs.

4.1.1 Ambient RH: Alone and With Low-Level Fumigation

Runs R04 and R05 were conducted at 40 percent RH, with and without low-level fumigation, respectively. Only two of the Category 2 materials were affected by these conditions, and fumigation with ClO_2 appears to have had no additional visual impact beyond that seen under ambient conditions alone.

Figure 4-1(a) shows that by year's end, very mild corrosion was seen on some of the connector screws in the breakers even under ambient conditions (without ClO_2 fumigation). The addition of 75 ppmv ClO_2 (Figure 4-1(b)) shows a very slight increase in corrosion. Figure 4-1(c) shows that increasing the RH to 90 percent (Run 08) resulted in just slightly more corrosion than the corrosion seen at 40 percent RH alone.

The second visual impact that could be seen was a very mild fading of the colors in the inkjet-printed pages over the year-long observation period. Once again, there seemed to be no additional visual damage caused by the 75 ppmv ClO_2 fumigation in run R04. The black printing was unaffected, and the last page of these 15-page stacks looked identical to the first. Figure 4-2 shows that the laser-printed paper (on the left) is still quite vibrant. The slight fading of the inkjet colors was not unexpected, as this decrease in color staying power is a known trade-off of this much less expensive printing option.

Table 4-1. Documented Visual Changes in Category 2 Materials

Material	Visual Change
Cu and Al services	Corrosion and wire insulation discoloration
Circuit breaker	Corrosion
Metal coupons	Corrosion
Laser- and ink jet-printed color papers	Fading, discoloration, loss of legibility
Photographs	Fading, discoloration
Drywall nails and screws	Corrosion
Stranded wire	Individual wire insulation discoloration and corrosion of wire ends
Housing insulation	Discoloration
Steel outlet/switch box	Corrosion
Sealants (caulk)	Discoloration
Gaskets	Discoloration
DSL conditioner	Discoloration
Smoke detector	Corrosion

No visual changes were noted for 300 series stainless steel, laser-printed paper, caulk sealant or gaskets under any of the test run conditions. The results are presented below in three groups according to the RH of the run condition: ambient (40 percent), standard fumigation conditions (75 percent) and high RH (90 percent). Within each group, the variations in visual effects are presented for each level of fumigation, whether control (0 ppmv), low (75 ppmv) or high (3,000 ppmv) ClO_2.

Table 4-2. Summary of Visual Changes Noted in Category 2 Materials

Temp, °C	**24**	**24**	**24**	**24**	**24**	**24**	**27**
RH	**40%**	**40%**	**75%**	**75%**	**90%**	**90%**	**88%**
ppmv	**0**	**75**	**75**	**3,000**	**0**	**3,000**	**3,000**
Test Condition[1]	**R05**	**R04**	**R03**	**R01**	**R08**	**R06**	**R07**
Cu and Al Services	---	---	Corrosion on edges	Corrosion on edges, mild Al service wire discoloration	---	Corrosion on edges, Al service wire discoloration	Corrosion on edges, Al service wire discoloration
Circuit Breakers	Very mild screw corrosion	Very mild screw corrosion	Mild screw corrosion	Mild screw corrosion	Mild screw corrosion	Screw corrosion	Screw corrosion
101 Copper coupons	---	---	Tarnish	Tarnish	---	**Severe corrosion**	**Severe corrosion**
Low carbon steel coupons	---	---	**Severe corrosion**	**Severe corrosion**	---	**Severe corrosion**	**Severe corrosion**
410 Stainless steel coupons	---	---	---	---	---	**Severe corrosion**	**Severe corrosion**
430 Stainless steel coupons	---	---	---	---	---	---	Corrosion
304 Stainless steel coupons	---	---	---	---	---	---	---
316 Stainless steel coupons	---	---	---	---	---	---	---
309 Stainless steel coupons	---	---	---	---	---	---	---
3003 Aluminum coupons	---	---	---	---	---	---	Chalky residue
Housing Insulation.	---	---	---	---	---	---	Discoloration
DSL connector	---	---	---	---	---	Discoloration	Discoloration
Steel outlet/ switch box	---	---	---	---	---	Chalky residue	---
Caulk sealant	---	---	---	---	---	---	---
Gaskets	---	---	---	---	---	---	---
Inkjet-printed paper	Very mild fading	Very mild fading	Moderate fading	Moderate fading	Very mild fading	**Severe Fading**	**Severe Fading**
Laser-printed paper	---	---	---	---	---	---	---
Photographs	---	---	Slight yellowing	**Severe fading**	---	**Severe Fading**	**Severe Fading**
Drywall nails	---	---	Mild corrosion	Mild corrosion	---	Corrosion	Corrosion
Drywall screws	---	---	Mild corrosion	Mild corrosion	---	Corrosion	Corrosion
Stranded wire	---	---	Tarnished wire ends	Tarnished wire ends	---	Corrosion	Corrosion
Smoke detector	---	---	---	---	---	Terminals corroded	Terminals corroded
Lamp switches	---	---	---	---	---	---	---

Note:

1. R02 data were not collected, nor are data presented here. Runs were aborted due to condensation issues.

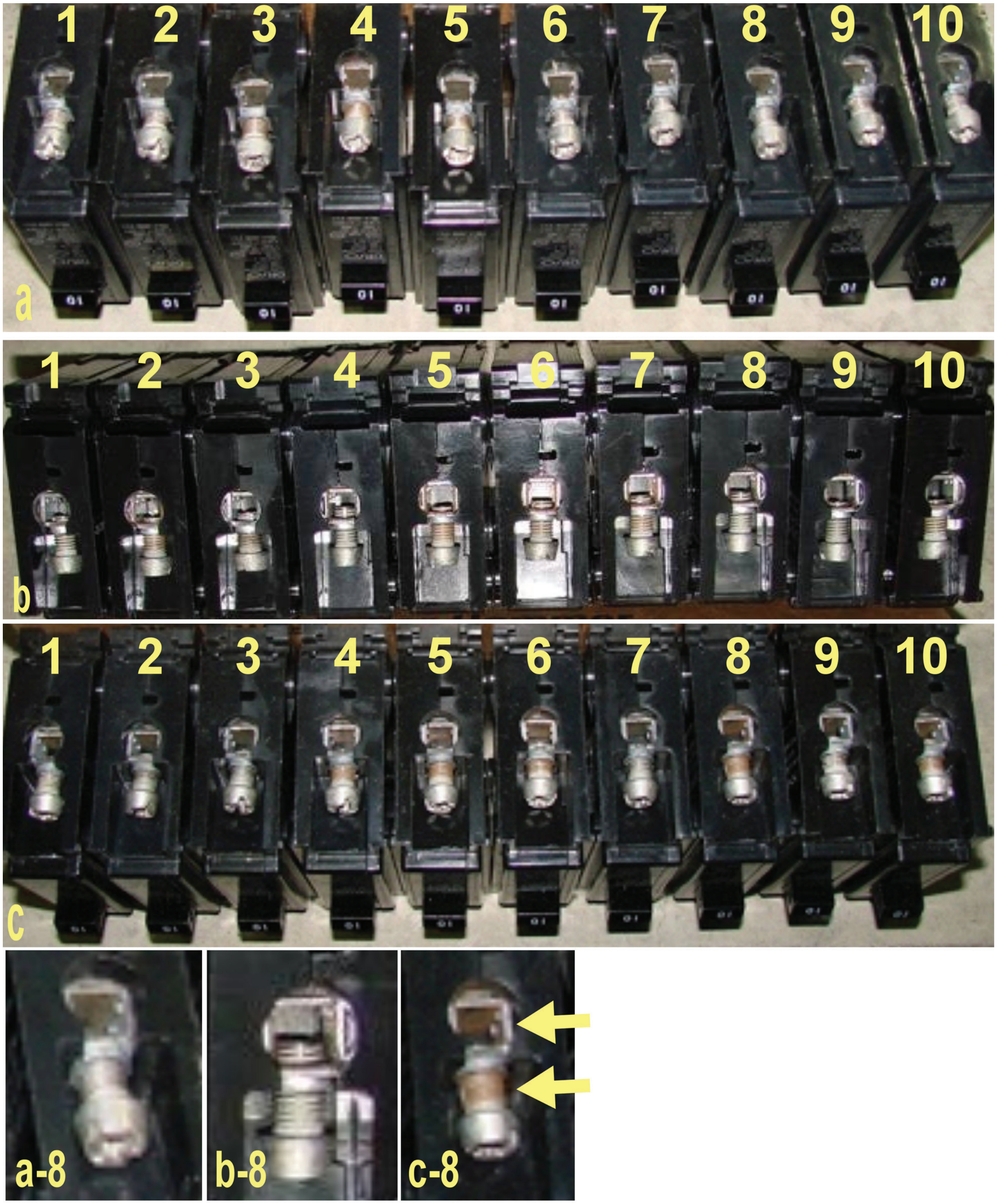


Figure 4-1. Corrosion on breaker screws at 12 months post exposure to (a) ambient conditions only (R05), (b) low RH fumigation (R04), and (c) high RH fumigation (R02); breakers are numbered 1-10 and a close-up of the screws for breaker 8 is shown. The arrows point to areas of corrosion evident on the screw on breaker 8 after exposure to high RH fumigation (labeled c-8 in the figure).

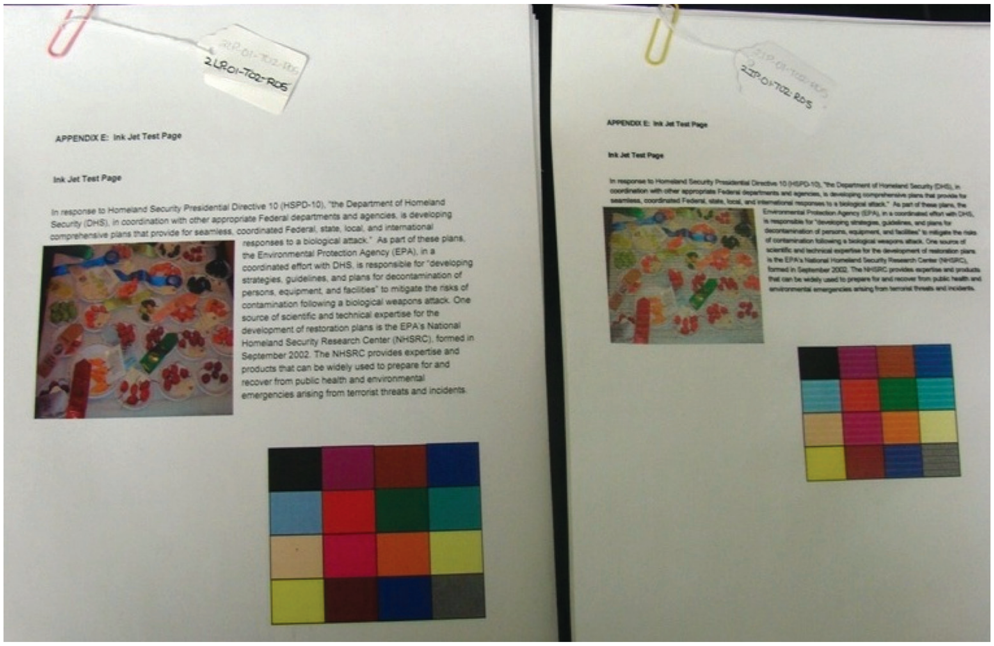


Figure 4-2. Laser (left) versus inkjet (right) color printed paper at 12 months post-exposure to ambient conditions (R05).

Impact of RH Alone and with Low-level Fumigation: Increasing the RH from ambient levels (40 percent) to almost condensation stage (90 percent), or operating at ambient RH levels with low-level fumigation (75 ppmv) seemed to have little or no impact beyond the natural degradation of this type of material over a one-year-long observation period.

4.1.2 Standard Fumigation RH: Low- and High-Level Fumigation

The next two runs were conducted at the standard fumigation RH of 75 percent and at both the low-level (75 ppmv ClO_2 in R03) and high-level (3,000 ppmv ClO_2 in R01) fumigation conditions. The majority of visual changes noted were similar between the two runs, but the visual changes were of a more severe nature for those materials exposed to the 3,000 ppmv ClO_2 fumigation.

The first visual change noted for the Al or Cu Services was corrosion on the edges of the steel box itself, seen in both of these 75 percent RH runs (75 and 3,000 ppmv ClO_2). Since the impact of high RH alone (90 percent RH) and low-level fumigation at ambient RH (75 ppmv ClO_2, 40 percent RH) seems to be insignificant, the combination of ClO_2 and elevated RH seems to be the cause of the observed corrosion along the exposed edges. Figure 4-3 shows this corrosion in both standard fumigation RH runs next to the unaffected 75 ppmv ClO_2, 40 percent RH run.

The second visual change was noted only in the Al service under the 3,000 ppmv ClO_2, 75 percent RH fumigation conditions. Although the change was difficult to see in the photographs, there was a mild green discoloration of the lighter beige wire insulation that was not seen in the 75 ppmv ClO_2, 75 percent RH fumigation.

The breakers in both of these runs experienced mild corrosion of the screws. At both fumigation concentrations for 75 percent RH this corrosion was very similar to the corrosion seen for the 0 ppmv ClO_2, 90 percent RH run shown in Figure 4-1(c).

The 101 copper coupons in both runs showed some mild discoloration (tarnish) by year's end. However, as shown in Figure 4-4, this discoloration does not appear to be much more than the discoloration that was seen on the R05 coupons which were maintained at ambient humidity and were not subjected to ClO_2 fumigation at all. This conclusion is supported by the lack of significant change in resistivity seen during the functionality tests.

The low carbon steel coupons fared among the worst of all the Category 2 and 3 materials at both of the 75 percent RH conditions. Figure 4-5 shows the severe corrosion which was apparent immediately following fumigation and which looked similar through the first five months. By year end, the corrosion had turned into a copious, flaking, rust-like covering.

The laser-printed paper continued to hold the colors well. However, the inkjet colors experienced moderate fading at both the 75 and 3,000 ppmv ClO_2 conditions. Figure 4-6 shows the first and last laser printed page (left side of each picture) next to the comparable inkjet-printed page. Being at the bottom of the stack of 15 sheets appears to have provided no protection from fading for the inkjet colors. The black printing was unaffected.

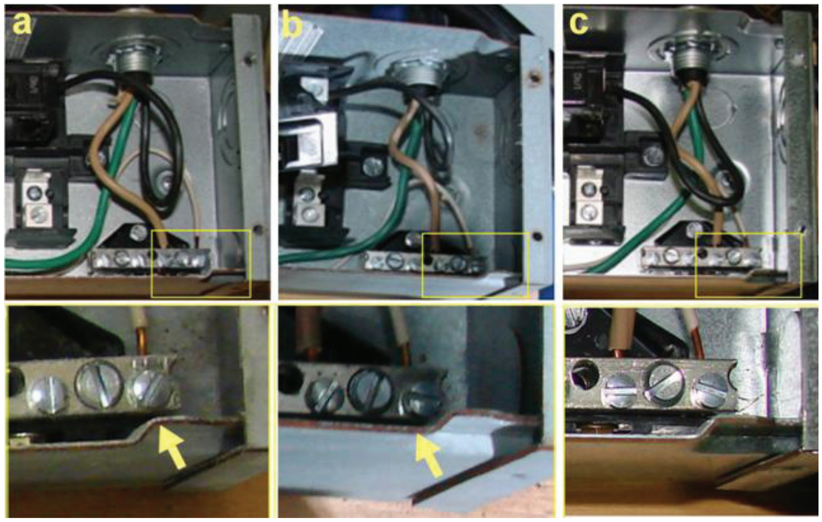


Figure 4-3. Corrosion on Cu service box at 12 months post-exposure to (a) low concentration fumigation (R03), (b) standard fumigation (R01), and (c) low RH fumigation (R04); lower pictures show a zoomed in area designated by the yellow boxes (arrows point out corrosion on edges of services).

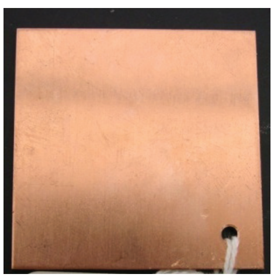
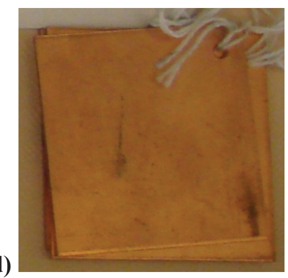
(a)  (b)  (c)  (d) 

Figure 4-4. 101 Copper coupon (a) before and 12 months after the exposure to (b) low concentration fumigation (R03), (c) standard fumigations (R01), and (d) ambient conditions only (R05).

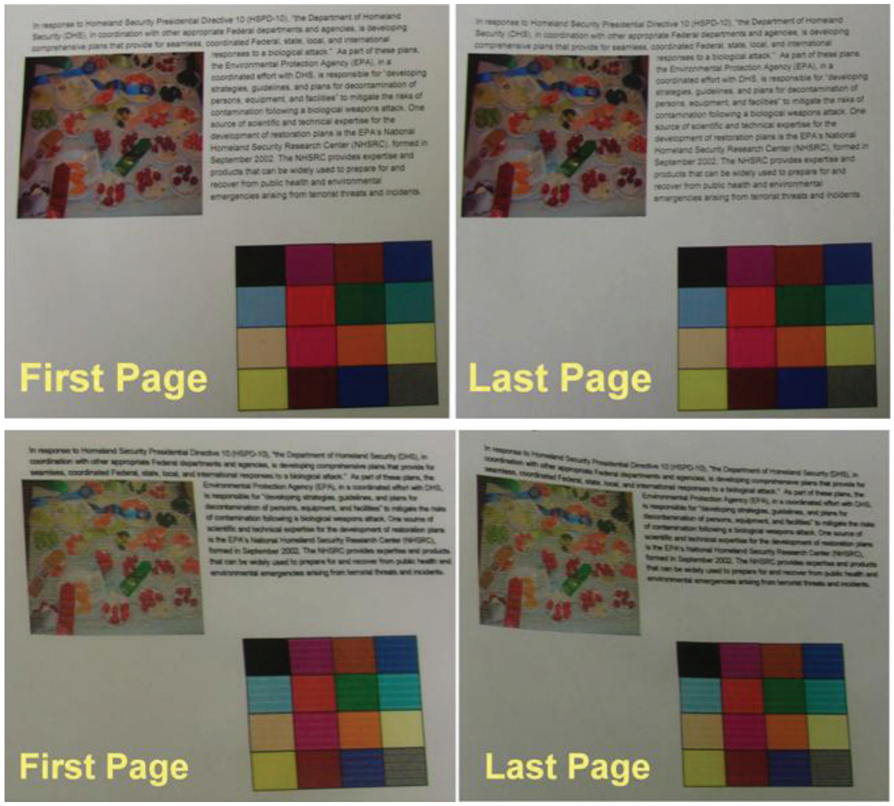

(a)


(b)


(c)


(d)

Figure 4-5. Low carbon steel coupon (a) before, (b) immediately after low concentration fumigation (R03), (c) immediately after standard fumigation (R01), and (d) 12 months post-exposure to standard fumigation (R01).



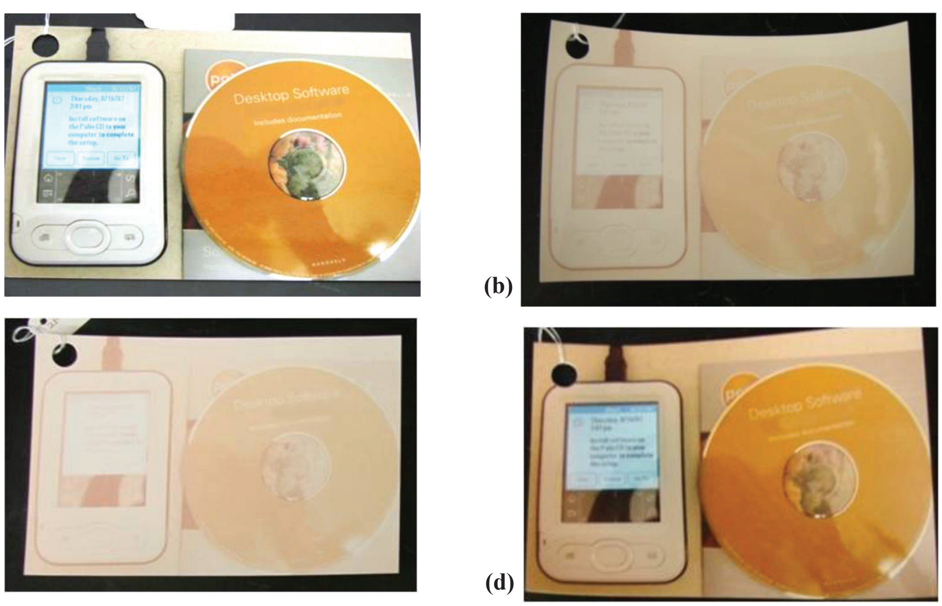
(a)

(b)

Figure 4-6. (a) Laser and (b) inkjet printed pages at 12 months post-exposure to standard fumigation (R01).

The photographs from the 75 ppmv ClO_2, 75 percent RH fumigation conditions were not faded, but did appear slightly discolored (yellowed) by year's end (Figure 4-7(d)). However, for the 3,000 ppmv ClO_2, 75 percent RH conditions, there was severe fading immediately following ClO_2 exposure. Although there was some further lightening by year end, the majority of the damage could be directly attributed to the fumigation process itself.

The only other visual effects noted for the standard fumigation RH runs were some mild corrosion on the drywall nails and screws, and some tarnish on the exposed ends of the stranded wire.



(a) (b)

(c) (d)

Figure 4-7. Photograph (a) before, (b) immediately after, and (c) at 12 months post-exposure to standard fumigation (R01), and (d) 12 months post-exposure to low concentration fumigation (R03).

Impact of Low- and High-Level Fumigation at Standard RH: Some Category 2 materials (as noted in Table 4-2) subjected to standard fumigation RH of 75 percent and to low (75 ppmv ClO_2, 900 ppmv-hour) and high (3,000 ppmv ClO_2, 9,000 ppmv-hour) level fumigation concentrations were significantly impacted. In most instances, the degree and type of degradation of specific materials were similar between the two runs, but of a more severe nature for those exposed to the higher level of fumigation. The most significant impacts were severe corrosion of the low carbon steel coupons in both runs, and severe fading of the photographs in the 3,000 ppmv ClO_2, 75 percent RH run.

4.1.3 High RH Fumigation: Control and High-Level Fumigations

Condensation was a recurring and ultimately unsolvable problem with the high RH runs. Because of condensation, a control run (R08) was conducted to document any effects caused by the 90 percent RH itself. The only visual effects noted were the mild screw corrosion on the breakers (as shown in Figure 4-1) and some mild fading of the inkjet colors, identical to the visual effects seen in the ambient RH control run (R05) and shown in Figure 4-2.

The final two runs were both 3,000 ppmv ClO_2 fumigations. Run R06 was conducted at 90 percent RH and 24 °C (75 °F). Because condensation was still present, a second run (R07) was conducted at a slightly reduced RH (88 percent) and a slightly elevated temperature, 27 °C (80 °F), to try to alleviate the problem. Although the condensation persisted, the control run (R08) showed that the moist conditions alone were not responsible for the much more severe and widespread damage noted for both of these 3,000 ppmv ClO_2 fumigations. The visual impacts noted for these two runs were similar, and of a higher magnitude than the visual impacts seen in the 75 percent RH fumigation runs.

As discussed earlier, the Al and Cu service boxes experienced corrosion on their edges. In addition, both Al services fumigated at the 3,000 ppmv ClO_2 and high RH conditions experienced a green discoloration of one of the wires that had been white insulation. This discoloration can clearly be seen in Figure 4-8. The breakers in both of the high fumigant, high RH runs experienced marked corrosion of the screws. Not unexpectedly, these harshest fumigation conditions caused more corrosion than had been seen under any of the other test scenarios (see Figure 4-1).

The 101 copper coupons were much more heavily impacted at the increased RH (see Figure 4-4 for the 3,000 ppmv ClO_2, 75 percent RH coupons) and appeared heavily corroded. Figure 4-9 shows the copper coupon before fumigation, immediately thereafter, and at the end of the one-year period.

(a) (b)

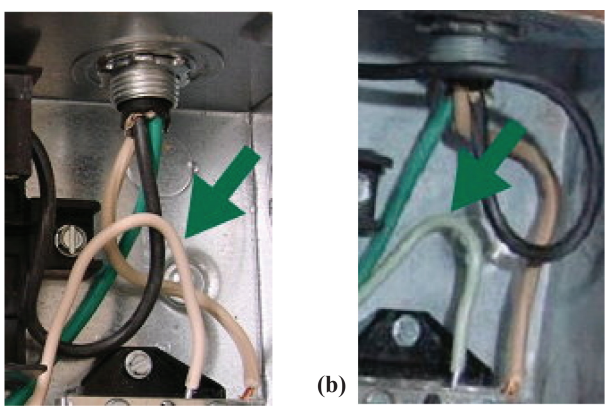


Figure 4-8. Al Service (a) prior to fumigation, (b) at 12 months post-exposure to high RH fumigation (R06); the arrows point to the originally white-cased wire that turned greenish in color after fumigation under R06.

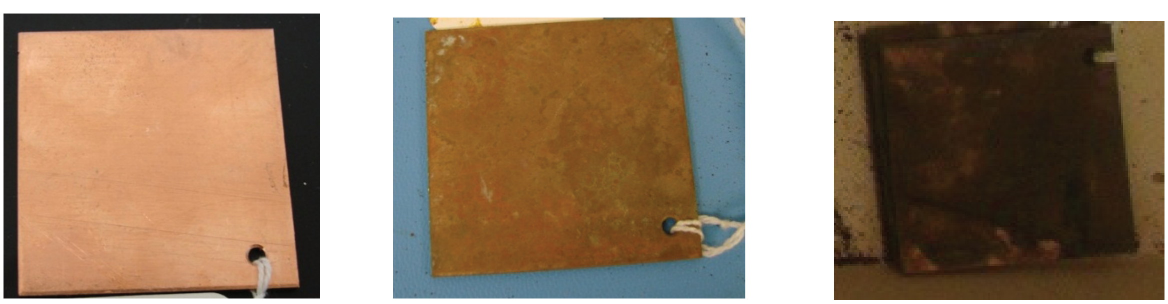


Figure 4-9. 101 Copper coupon (a) before, (b) immediately after, and (c) at 12 months post-exposure to high RH fumigation (R06).

The low carbon steel coupons experienced the same severe corrosion as seen at the 75 percent RH conditions (see Figure 4-5). The 410 stainless steel coupons were also severely corroded as shown in Figure 4-10.

Figure 4-10. 410 Stainless steel coupons (a) before, (b) immediately after, and (c) at 12 months post-exposure to high RH fumigation (R06).

Three visual differences were noted between these two high-concentration, high RH runs. The first difference was seen in the 430 stainless steel coupons. The slightly elevated temperature in run R07 (27 versus 24 °C) apparently caused some corrosion on the 430 stainless steel coupons that was not seen in the R06 coupons. The RH was actually lower in R07 (88 versus 90 percent), indicating the increased temperature as the cause of the corrosion seen in Figure 4-11.

Figure 4-11. 430 Stainless steel coupons (a) before, (b) immediately after, and (c) at 12 months post-exposure to high RH fumigation (R07.)

The second visual change apparently caused by the elevated temperature in run R07 was observed in the 3003 aluminum coupons. Although it is not apparent in Figure 4-12 below, there was a chalky residue on these coupons. This layer interfered with the ability of the coupon to conduct electricity and resulted in an unstable reading at the year-end testing. Otherwise, no observed differences were noted (Figure 4-12).

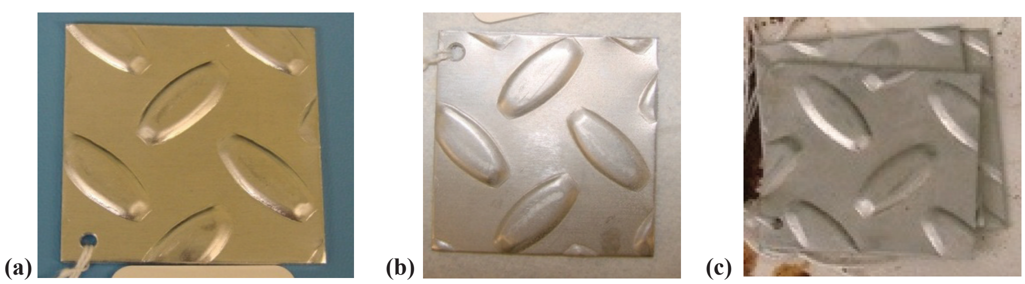
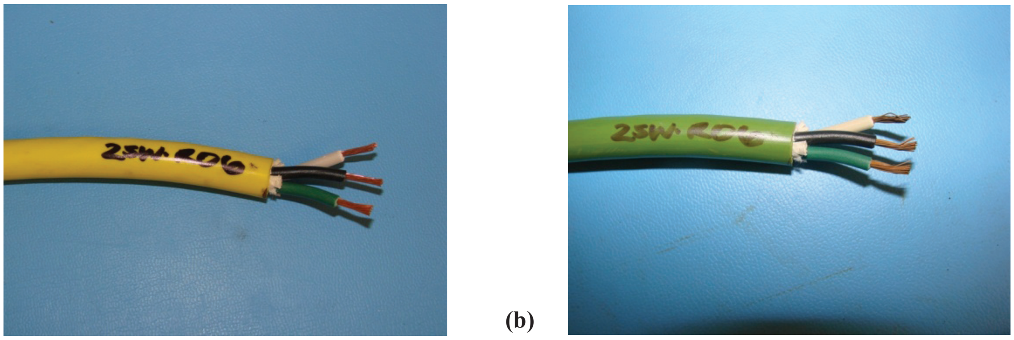


Figure 4-12. 3003 Aluminum coupons (a) before, (b) immediately after, and (c) at 12 months post-exposure to high RH fumigation (R07).

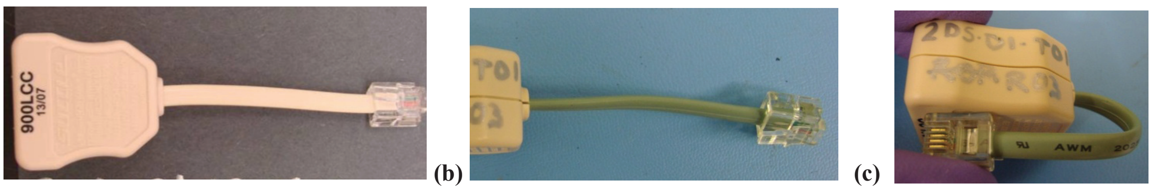
The final visual change noted in the R07 run and apparently caused by the elevated temperature was that the housing insulation covering the stranded wire turned green as shown in Figure 4-13. This discoloration was not seen in any of the other runs.



(a) (b)

Figure 4-13. Strand wire (a) prior to and (b) immediately following the high RH fumigation (R07); note discoloration of the housing insulation.

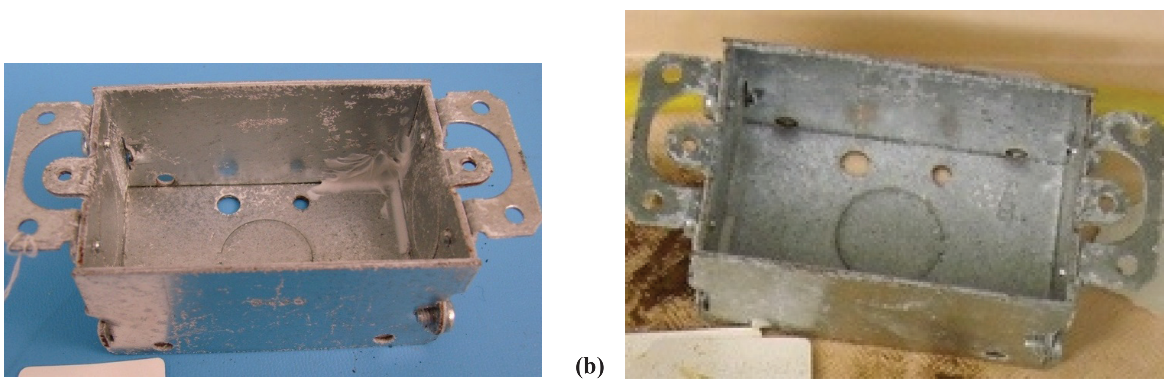
Interestingly, there was discoloration of the DSL connector during both high-humidity, high fumigation runs. As with the housing insulation for run R07, the insulation turned green, as shown in Figure 4-14.



(a) (b) (c)

Figure 4-14. DSL connector (a) before, (b) immediately after, and (c) at 12 months post-exposure to high RH fumigation (R06).

There was just one visual change that was unique to run R06 (3,000 ppmv ClO_2, 90 percent RH, and 24 °C). A chalky white residue was found on the steel outlet/switch box at month five and can clearly be seen in Figure 4-15. The right-hand photograph shows that the residue worsened only slightly by year end.



(a) (b)

Figure 4-15. Chalky white substance found on the steel outlet/switch box (a) at 5 months and (b) 12 months post-exposure to high RH fumigation (R06).

The combination of the 3,000 ppmv ClO_2 fumigation with high RH, both at 24 and 27 °C, led to immediate and severe damage to both inkjet colors and to the photographs. Quality did not appear to be further degraded over the next year, and the last pages of the 15-page stacks looked very similar to the first. The inkjet black printing was still clearly legible, and the laser-printed colors remained quite vibrant throughout. Figures 4-16 and 4-17 show the impacts of high-level, high humidity fumigation on inkjet printed papers and on photographs, respectively.

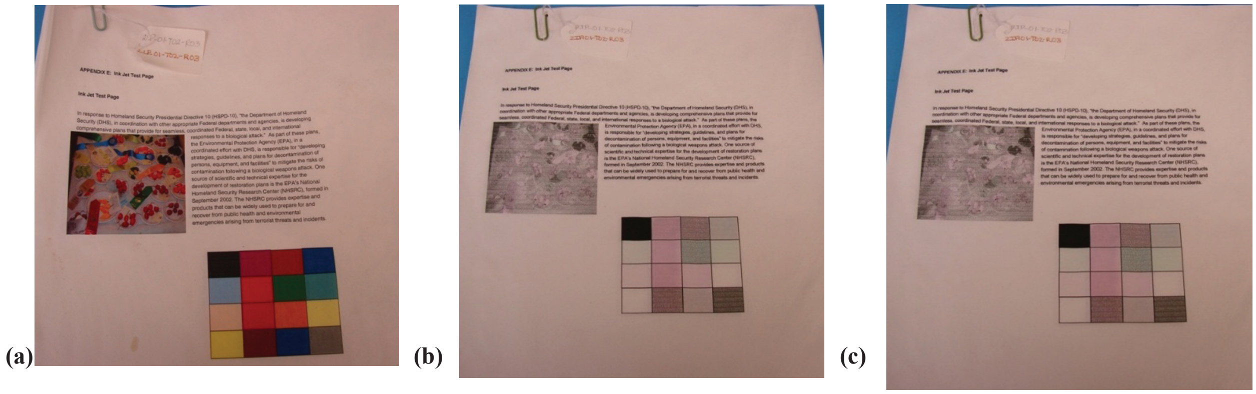


Figure 4-16. Results of high RH fumigation (R06) shown for (a) laser printed paper at 12 months post-exposure, (b) inkjet printed pages immediately after exposure, and (c) inkjet printed pages at 12 months post-exposure.

Figure 4-17. Photographs (a) before, (b) immediately after, and (c) 12 months post-exposure to high RH fumigation (R06).

The ClO_2 fumigation caused some mild corrosion of the drywall nails and screws at 75 percent RH. At the high RH of runs R06 and R07, corrosion could be clearly seen on both by the end of the year as shown in Figure 4-18.

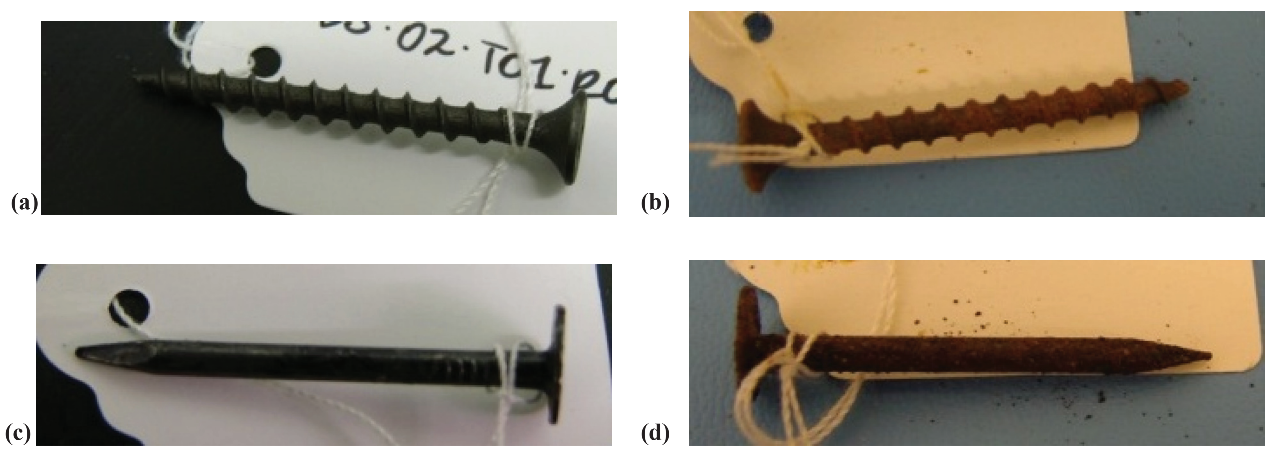
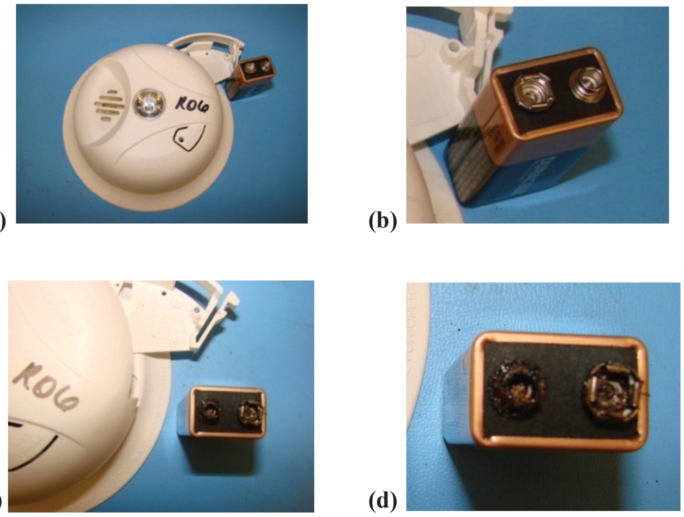


Figure 4-18. Results of exposure to high RH fumigation (R06) for (a, b) drywall screws (a – before and b – 12 months post-exposure) and (c, d) nails (c – before and d – 12 months post-exposure).

Although difficult to see in the photographs, the ends of the stranded wire became tarnished from the high level, high RH fumigation, as noted in both high RH runs. The smoke detectors in both high level, high RH runs experienced severe corrosion of the battery terminals, noted immediately following the fumigations and seen in Figure 4-19.



(a) (b) (c) (d)

Figure 4-19. Smoke detector (a) before and (c) immediately after exposure to high RH fumigation (R06); close-up of battery (b) before exposure and (d) immediately following fumigation.

Impact of the Combination of High RH and High Fumigation Settings: The Category 2 materials subjected to high RH (88 or 90 percent) and high fumigation concentration (3,000 ppmv ClO_2) experienced degradation that was visible; many of the effects were severe in nature. In both runs, severe corrosion was seen not only on the low carbon steel coupons but on the 101 copper coupons and 410 stainless steel coupons. The inkjet color pages and the photographs experienced severe fading, and corrosion was seen on the copper and aluminum services, breakers, the drywall nails and screws, the stranded wire, and on the smoke detector battery terminals. In addition, both runs showed wire discoloration in the aluminum services and in the DSL connector.

4.2 Category 3 Materials

The visual changes documented in Category 3 materials are detailed in Table 4-3. A summary of the noted visual changes by run number (condition) is shown in Table 4-4. Impacts were observed only for the high ClO_2 concentration, high RH runs.

Table 4-3. Documented Visual Changes in Category 3 Materials

Material	Visual Change
PDAs and Cell Phones	Screen discoloration or keypad corrosion
Fax machines	Keypad, terminal, or internal corrosion
DVDs and CDs	Label or play side discoloration or corrosion

Table 4-4. Summary of Visual Changes Noted in Category 3 Materials

Temp, °C	24	24	24	24	24	24	27
RH	40%	40%	75%	75%	90%	90%	88%
ppmv	0	75	75	3,000	0	3,000	3,000
Test Condition[1]	R05	R04	R03	R01	R08	R06	R07
PDA	—	—	—	—	—	—	—
Cell Phone	—	—	—	Mild Discoloration	—	Discolored/ faded screen	Discolored/ faded screen
Fax	—	—	—	—	—	**Severe printer bar corrosion**	**Severe printer bar corrosion**
DVD	—	—	—	—	—	—	—
CD	—	—	—	—	—	—	Thinned coating

Note:
1. R02 data were not collected, nor are data presented here. Runs were aborted due to condensation issues.

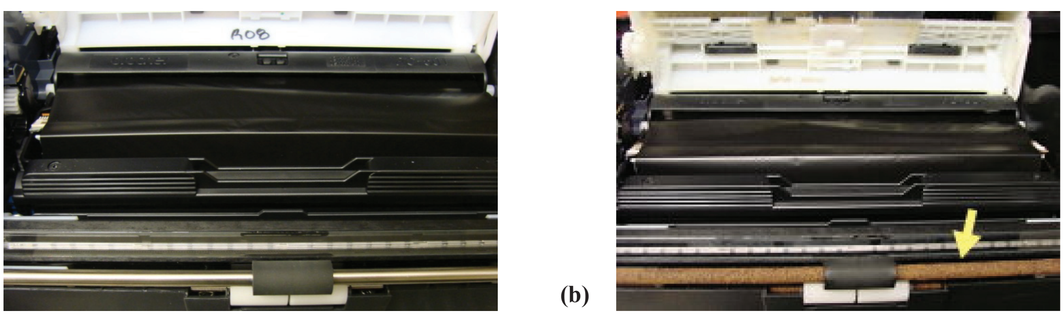
As Table 4-4 shows, very few visual changes were observed for the Category 3 materials. No visual changes were noted for either the PDAs or the DVDs, and neither of these items had any functional issues.

The only visual change noted for the cell phones was related to screen discoloration seen at the higher level fumigations. The screen legibility did not appear to be compromised. While milder at 75 percent RH, the effect was more marked in the high humidity runs, as can be seen in Figure 4-20.

(a) (b)

Figure 4-20. Cell phone screen (a) before and (b) at 12 months post-exposure to high RH fumigation (R06).

The fax machines at the high ClO_2 concentration, high RH runs showed severe corrosion of the metal printing bars which are exposed at the front of each machine. Figure 4-21 shows this bar as being unaffected on the machine subjected to 90 percent RH only (left), whereas the machine exposed to 3,000 ppmv, 90 percent RH conditions (right) is severely corroded.

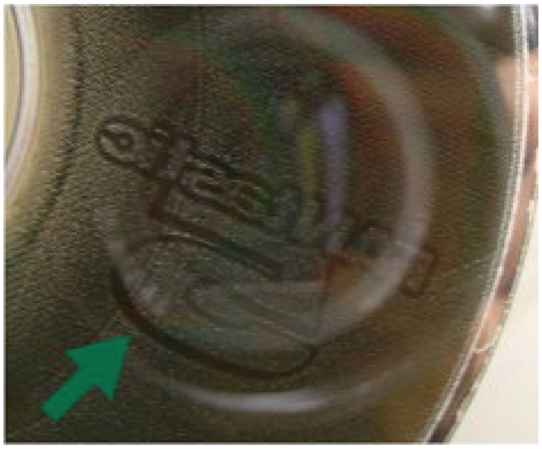


(a) (b)

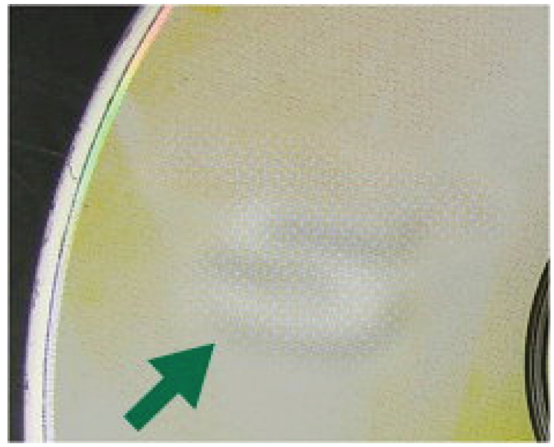
Figure 4-21. Fax machines at 12 months post-exposure to (a) high RH only (R08) and (b) high RH fumigation (R06); arrow in photo (b) shows corrosion on the printing bar.

The only CD with functional issues was seen in Run R07 (3,000 ppmv ClO_2, 88 percent RH, and 27 °C). At first inspection, there appeared to be no apparent visual evidence to explain why the CD would not play. However, after a closer inspection, these harshest of all fumigation conditions actually seem to have thinned the coating on the CD. Figure 4-22 shows that the label from the front of the disk can now be seen from the back of the CD. The coating on the CD had thinned – or perhaps been chemically altered to become more transparent – and the front label could be seen from the back side of the disk.

__Impact of ClO_2 Decontamination on Category 3 Materials:__ Except for some mild cell phone screen discolorations seen at 3,000 ppmv ClO_2 and 75 percent RH (run R01), the only visual impacts were encountered under the harshest decontamination settings (3,000 ppmv ClO_2 and RH > 88 percent). In both runs R06 and R07, the cell phone screen became faded and markedly discolored by year's end (Figure 4-20). In addition, severe corrosion of the exposed printer bar at the front of the fax machines for both runs was observed (Figure 4-21). However, once again, the slight increase in run temperature for R07 (27 versus 24 °C) caused degradation that was seen only under these conditions.



(a)



(b)

Figure 4-22. (a) Back and (b) front of the CD after high RH fumigation (Run 07); arrow points to the label on the CD front that has faded and is now visible on the back surface.

4.3 Category 4 Equipment

The visual changes documented for Category 4 equipment are detailed in Table 4-5. A summary of the noted visual changes by run number (condition) is shown in Table 4-6.

Table 4-5. Documented Visual Changes in Category 4 Equipment

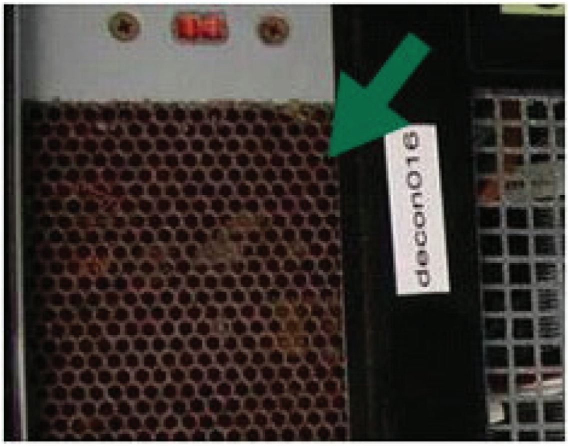
Equipment	Visual Change
Desktop computer	Corrosion and residue (outside and inside)
Computer monitor	Discoloration and residue
Computer keyboard	None
Computer power cord	Some corrosion
Computer mouse	None

No visual changes were noted for the monitors, keyboards, power cords or the mice, with the exception of some corrosion on the power cord plug copper contacts at the 3,000 ppmv ClO_2 fumigations, and some monitor screen discoloration at the harshest conditions (3,000 ppmv, 90 percent RH). The plastics used for these components seem to be unaffected by even the high ClO_2, high RH conditions.

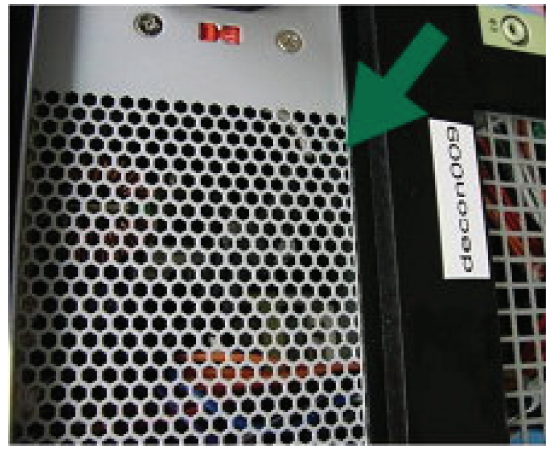
The only external visual evidence on the computers themselves was severe corrosion (rust) of the grid on the back of the computers exposed to 3,000 ppmv of ClO_2. Figure 4-23 shows this grid from the computer exposed to the 3,000

Table 4-6. Summary of Visual Changes Noted in Category 4 Equipment

Temp, °C	**24**	**24**	**24**	**24**	**24**	**24**	**24**
RH	**40%**	**40%**	**75%**	**75%**	**75%**	**90%**	**90%**
ppmv	**0**	**75**	**75**	**3,000, Off**	**3,000, On**	**0**	**3,000**
Test Condition	**7**	**6**	**5**	**1**	**2**	**4**	**3**
Desktop Computer			Some internal dust	Rust on metal grid on back. **Internal dust.** Wire discoloration	Rust on metal grid on back. **Internal dust.** Wire discoloration		Rust on metal grid on back. **Internal dust.** Wire discoloration
Computer Monitor							Screen discoloration
Computer Power Cord				Plug corrosion	Plug corrosion		Plug corrosion



(a)



(b)

Figure 4-23. Rust on the stamped metal grid on the back of the computer at 12 months post exposure to (a) high RH fumigation (R06) compared to the lack of rust observed due to exposure to (b) high RH only (R08); arrow points to the grid.

ppmv ClO_2, 90 percent RH conditions. This figure also shows this same grid from the back of the computer exposed to 90 percent RH only (no fumigation), showing that this corrosion is a direct result of the ClO_2 exposure.

Large amounts of dust were observed inside many computers after fumigation, particularly at the higher ClO_2 concentrations. Alcatel-Lucent used scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) to determine the morphology and elemental composition of the dust.[15]

Per Alcatel-Lucent's analysis and conclusions[15], four prevalent types of corrosion particles were found:

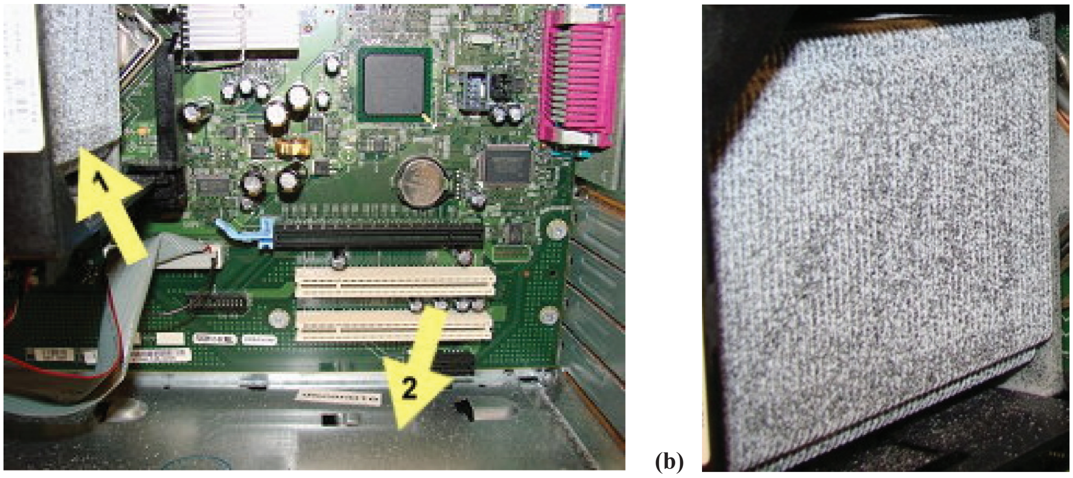
- **Al-Cl**: These particles are spherical and consist of aluminum, chlorine, oxygen, and carbon. The particles have smooth surfaces that appear to have undergone hydrolysis and dehydration.
- **Al-Ni**: The Al-Ni particles are rough and platelet-like, consisting of aluminum, chlorine, oxygen, nickel, phosphorus, and carbon. The Al-Ni particles appear to be agglomerates of finer particles. The source of these particles was also the nickel coated central processing unit (CPU) aluminum heat sink.
- **Fe**: The Fe particles are smooth-surfaced and hygroscopic, consisting of iron, zinc, chlorine, oxygen, and carbon. The potential source of these Fe-containing corrosion particles was the multiple iron-containing metal surfaces, including the case sheet metal, metal hardware, and the motherboard battery.
- **Ni**: The Ni particles are coarse, consisting of nickel, zinc, copper, chlorine, oxygen, and carbon. These particles are found adhering to corroded surfaces and are not found distributed elsewhere inside or outside the computers. The primary source of these nickel corrosion particles was the rear connector nuts.[15]

This dust was formed only on the CPU heat sink, and not on the graphics processing unit (GPU) heat sink. Alcatel-Lucent noted:

> *The low degree of corrosion of the GPU heat sink in comparison with the CPU heat sink is most probably due to the lack of galvanic corrosion. In contrast to the CPU heat sink which is made of aluminum alloy coated with nickel phosphorus ball, the GPU heat is made of a single aluminum alloy.[15]"*

The compatibility of any aluminum-containing equipment with ClO_2 fumigation may be difficult to determine without details of the composition of specific alloys of aluminum used in the equipment.

Because the PC-Doctor® testing protocol required opening the computer chassis, the dust inside the computer chassis presented a safety hazard to operators. The computers were placed on an anti-static mat within a hood and vacuumed out during monthly PC-Doctor® tests. The cleaning operation may have improved the operation of the computers by removing hygroscopic particles that could have conducted or shorted any electrical components within the chassis. However, removal of this dust was only a temporary solution since new dust continued to be either formed or released over time while the computers sat in ambient room air. Figure 4-24 shows the inside of one of the computers fumigated at 3,000 ppmv ClO_2 and 90 percent RH during the year-end testing. Even with repeated vacuuming, dust can still be seen on the floor of the computer. The dust accumulation on and below the CPU heat sink makes the heat sink the obvious source of the particles still being seen a full year after the ClO_2 fumigation.



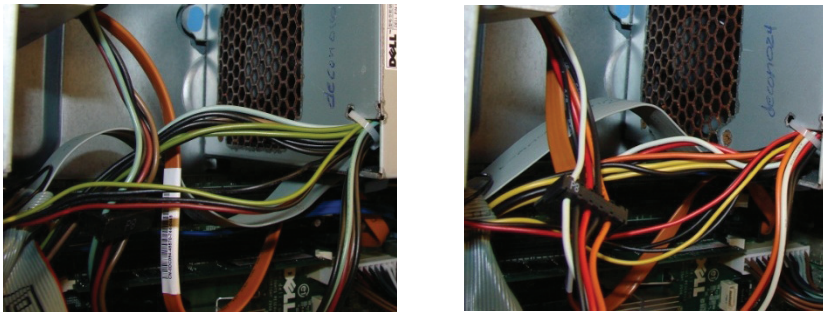
(a) (b)

Figure 4-24. (a) Inside of computer at 12 months post-exposure to high RH fumigation (R06) (Arrow 1 points to dust on the heat sink and Arrow 2 to dust particles on the bottom of the case); (b) close-up of the heat sink.

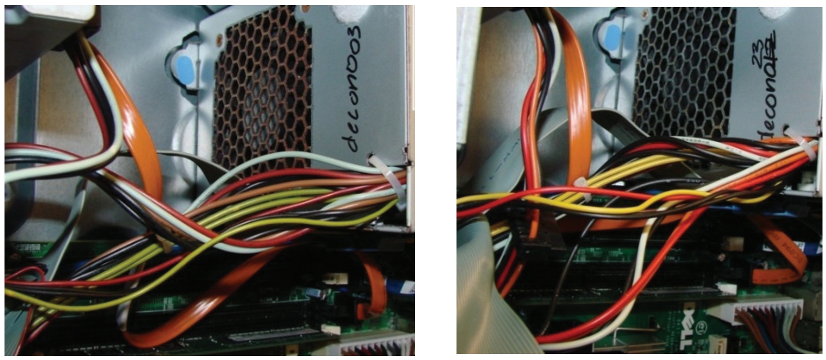
For some of the wire insulation in the Category 2 materials, discoloration was found in the high ClO_2 fumigation runs. However, Figure 4-25 shows that only one of each set of computers at each 3,000 ppmv ClO_2 condition (the third having been sent to Alcatel-Lucent) showed the wire insulation discoloration. The location within the chamber seems to be the factor determining whether or not a computer has the discoloration – the computer more to the right is more discolored than the computer that was placed more to the left. The left-hand side is closer to the ClO_2 injection point and the right-hand side is closer to the humidity injection and fresh air intake. Because there is no trend of RH or temperature within the computers based on location, the evidence indicates complex ClO_2 gradients within the chamber despite the mixing fans. While not ideal, such gradients are not considered atypical of actual fumigation events for larger structures.

In Figure 4-25, comparing the left and right computers with each test condition (Figure 4-25 a, b, c) shows the difference in coloring of some of the wiring due to position in the chamber during exposure to ClO_2 at the defined conditions. The most easily observable differences in the photos are for the yellow wires (right figures) that have more of a greenish tint than in the left figures. Other color changes were also apparent, but are more difficult to discern from the photos. The 75 ppmv ClO_2, 75 percent RH computers appear to have been unaffected.

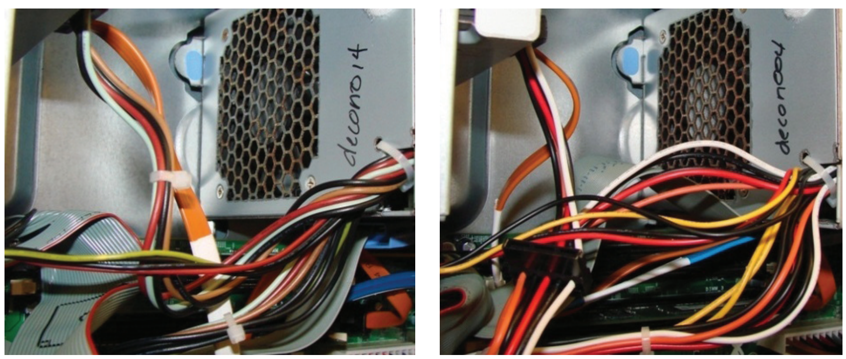
<u>Impact of ClO_2 Decontamination on Category 4 Equipment:</u> The major visible damages experienced by the tested computers and their respective ancillary equipment were discoloration of the internal wires and dust formation inside the computer casing. These damages were encountered primarily at the high concentration ClO_2 fumigation settings (3,000 ppmv ClO_2, RH > 75 percent). Although the low concentration ClO_2 fumigation setting (75 ppmv ClO_2, 75 percent RH) did have some visible internal dust, there was no apparent discoloration of the wires.



(a) High RH fumigation (Test 3), ON condition (decon016 [left] and decon024 [right])



(b) Standard Fumigation (Test 2), ON Condition (decon003 [left] and decon023 [right])



(c) Standard Fumigation (Test 1), OFF Condition (decon014 [left] and decon004 [right])

Figure 4-25. Effects on computer wiring at (a) high RH fumigation with the computers in the ON power state (Test 3); (b) standard fumigation with the computers in the ON power state (Test 2) and (c) standard fumigation with the computers in the OFF power state (Test 1).

5.0 Data Analysis/Functionality Tests

The results of functionality tests were reviewed for each material pre-exposure, immediately post-exposure, and then monthly thereafter for a period of one year looking for instances of intermittent or repeated failures. The only exceptions were for Category 2 and 3 materials (which were tested monthly for five months, then again at year's end) and Category 4 equipment (which was tested every month except for months 9 and 11). These tests ranged from simple stress tests performed on gaskets to the highly detailed PC-Doctor® Service Center™ 6 testing conducted on the Category 4 computers. Where changes were noted, all visual files and written documentation were reviewed to provide a detailed understanding of the effects of fumigation and the different run conditions on that material/component. For the Category 4 computers, failures are identified by the component parts themselves (such as CDs and DVDs) as well as the sub-component parts that are most likely to lead to failure of that component.

5.1 Category 2 Materials

Functional changes, as appropriate, were sought in the Category 2 materials as detailed in Table 5-1. Table 5-2 details those changes by run number (condition).

Table 5-1. Documented Functional Changes in Category 2 Materials

Material	Functional Change
Cu and Al Services	Time to failure
Circuit breaker	Time to failure
Metal coupons	Change in resistance
DSL conditioner	Phone would not work through this connection
Sealants (caulk)	Leakage (failure of caulk to seal)
Gaskets	Simple stress test (decreased integrity when bent)
Switches (lamp)	Bulb would not light
Stranded wire	Change in resistance
Smoke detector	Failure of battery and smoke test; failure of light function

The breakers used in the Cu and Al services were the same 10 amp breakers that were tested alone. Originally, the breakers (10 per run condition) and services were tested at 15 amps (or 150 percent). However, the minimum to maximum time range to failure under these conditions is from 40 seconds to 16.6 minutes. Because of the large number of breakers requiring testing, the breaker testing conditions were changed to 20 amps (200 percent). This change lowered the acceptable range of failure time from 10 to 100 seconds.

One of the individual breakers from runs R03, R06, and R07 was found to be cracked at different periods throughout the year, but the cracks did not appear to affect the functionality. These cracks may be an effect of the rigors of the testing procedure and not of the fumigation. Under all fumigation scenarios, the services and individual breakers tripped within the manufacturers' established breaker curves for their respective loads.

The low carbon steel coupons suffered severe corrosion during run R03 (75 ppmv ClO_2, 75 percent RH) and during all of the high-level, 3,000 ppmv ClO_2 fumigations (R01, R06 and R07). This surface corrosion caused increased contact resistance, making resistance measurement of the base metal unreliable. The high-level, high RH runs (R06 and R07) caused the same problems with the 101 copper coupons and the 410 stainless steel coupons.

Surprisingly, the slight increase in temperature of R07 (27 °C) over R06 (at 24 °C) resulted in corrosion of the 430 stainless steel coupons and in a chalky residue on the 3003 aluminum coupons, both of which resulted in unstable resistance measurements. Apparently the corrosive nature of ClO_2 is exacerbated by an increase in temperature, as well as by absolute humidity.

An intermittent failure of the sealant occurred in run R03 (75 ppmv ClO_2, 75 percent RH). Figure 5-1 shows the steel outlet/switch box with the sealant both before fumigation and at one year after fumigation. There is no discoloration, obvious pulling away from the surface, or other visual indication of failure. Corrosion can be seen in the unfinished and unsealed edges of the box; the arrows in Figure 5-1 point out some of the observed corrosion. These surfaces were not sealed.

During the control test at 90 percent RH (0 ppmv ClO_2), the smoke detector failed the smoke test and light function test at three months. The smoke detector passed all three tests every other time it was tested. However, in run R06 (3,000 ppmv ClO_2, 90 percent oRH), the smoke detector failed following fumigation, and the battery, smoke and light function tests failed from the one month testing through the end of the year. In run R07 (3,000 ppmv ClO_2, 88 percent RH) all tests failed post-fumigation. Figure 4-21 showed the battery terminal

Table 5-2. Summary of Functional Changes Noted in Category 2 Materials

Temp, °C	**24**	**24**	**24**	**24**	**24**	**24**	**27**
RH	**40%**	**40%**	**75%**	**75%**	**90%**	**90%**	**88%**
ppmv	**0**	**75**	**75**	**3,000**	**0**	**3,000**	**3,000**
Test Condition† 1	**R05**	**R04**	**R03**	**R01**	**R08**	**R06**	**R07**
101 Copper coupons	---	---	---	---	---	N/A	N/A
Low carbon steel coupons	---	---	N/A	N/A	---	N/A	N/A
410 Stainless steel coupons	---	---	---	---	---	N/A	N/A
430 Stainless steel coupons	---	---	---	---	---	---	N/A
3003 Aluminum coupons	---	---	---	---	---	---	N/A
Sealant (caulk)	---	---	Intermittent failure	---	---	---	---
Smoke detector	---	---	---	---	Intermittent failure	**FAILED**	**FAILED**
Light (switch)	---	---	---	---	---	---	Intermittent failure
Cu and Al Services	---	---	---	---	---	---	---
Circuit Breakers	---	---	---	---	---	---	---
304 Stainless steel coupons	---	---	---	---	---	---	---
316 Stainless steel coupons	---	---	---	---	---	---	---
309 Stainless steel coupons	---	---	---	---	---	---	---
Housing insulation.	---	---	---	---	---	---	---
DSL connector	---	---	---	---	---	---	---
Steel outlet/ switch box	---	---	---	---	---	---	---
Gaskets	---	---	---	---	---	---	---
Inkjet paper	---	---	---	---	---	---	---
Laser-printed paper	---	---	---	---	---	---	---
Photographs	---	---	---	---	---	---	---
Drywall nails	---	---	---	---	---	---	---
Drywall screws	---	---	---	---	---	---	---
Stranded wire	---	---	---	---	---	---	---

Notes:
N/A = Not available due to unreliable resistance measurements. Increased contact resistance from surface corrosion made resistance measurement of the base material unstable and/or unreliable.
† Test condition refers to column "Run Name" of Table 3-5.
1. R02 data were not collected, nor are data presented here. Runs were aborted due to condensation issues.

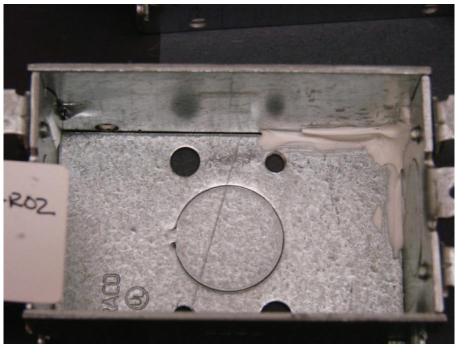
(a)  (b) 

Figure 5-1. Steel outlet/switch box (a) before fumigation and (b) at 12 months post-exposure to low concentration fumigation (R03); the white sealant can be observed in the upper right hand corner of the steel outlet/switch box.

corrosion caused by this combination of humidity and ClO_2. During the year-end testing, the battery was changed in both of these nonfunctioning smoke detectors. In R06, this battery change made no difference and the unit again failed all tests. However, in R07, once a new battery was installed, the smoke detector proceeded to pass all three function tests.

The light switch in R07 (3,000 ppmv ClO_2, 88 percent RH) failed to work during both the one- and two-month testing. A new bulb was tried both times to verify that the switch was failing. However, this failure was intermittent, as on month three and every month thereafter, the switch functioned properly and would light the bulb.

5.2 Category 3 Materials

The functional changes in Category 3 materials are detailed in Table 5-3. Table 5-4 details those changes by run number (condition).

Table 5-3. Functional Tests for Category 3 Materials

Material	Functional Change
PDAs	Inability to import and export files via synchronization with personal computer
Cell Phones	Inability to receive (incoming) and make (outgoing) calls, changes to ring and audio
Fax machines	Inability to receive (incoming) and send (outgoing) faxes; inability to receive (incoming) and make (outgoing) calls on telephone
DVDs	Inability to perform Read and Seek functions, tested via audio and visual checks of each chapter
CDs	Inability to perform Read and Seek functions, tested via audio checks of each song

Table 5-4. Summary of Functional Changes Noted in Category 3 Materials

Temp, °C	24	24	24	24	24	24	27
RH	40%	40%	75%	75%	90%	90%	88%
ppmv	0	75	75	3,000	0	3,000	3,000
Test Condition† 1	R05	R04	R03	R01	R08	R06	R07
PDA	---	---	---	---	---	---	---
Cell Phone	---	---	---	---	---	Intermittent failure	Intermittent failure
Fax	---	---	---	---	---	Intermittent send noise	Send failure and send noise
DVD	---	---	---	---	---	Loud humming noise	Loud humming noise
CD	---	---	---	---	---	---	**Failed to Read**

Notes:
† Test condition refers to column "Run Name" of Table 3-5.
1. R02 data were not collected, nor are data presented here. Runs were aborted due to condensation issues.

The PDAs were the single item in this category that had no functional problems over the one year testing period. In all of the fumigation scenarios, only the high ClO_2 concentration, high RH runs (R06 and R07) resulted in functional problems.

For both runs R06 and R07, the only visual indication of impacts on the cell phones from the fumigation was screen discoloration (see Figure 4-22), and operational problems were intermittent. In R06, the buttons were noticeably harder to use just one month after ClO_2 exposure. During the two-month post-fumigation testing, the phone would ring, but many of the keys were inoperative. Incoming audio and outbound ring and audio were not working. However, at months four and five, and again at year's end, all functional tests were passed. These observations indicate that at least some of the damage noted is reversible, probably due either to removal or drying of hydroscopic particles formed during fumigation.

The cell phone from R07 showed similar failures at month two. The phone could not be answered and outgoing calls could not be made due to the failure of certain keys on the keypad. All tests passed at month four. However, at the five-month post-fumigation testing, a marked drop in the audio level was noted. This drop in the audio level was the only functional issue noted at the year-end testing.

The visual evidence documented for the Category 2 and 3 materials indicated that the slight increase in fumigation temperature between runs R06 and R07 (from 24 to 27 °C) increased the detrimental effects of the high concentration ClO_2 fumigation under high RH conditions. The fax machines from runs R06 and R07 provide a good example of this effect.

The only operational problem encountered with the fax from run R06 was an intermittent internal noise when sending a document (at month three and again at year's end). In run R07, a consistent problem of only being able to send one-half of a page started immediately after the fumigation and persisted throughout the year. Like the R06 fax, a noise when sending a document started at month three. But in this case, the noise turned into a loud clicking by month five. Both of these faxes had severe corrosion on the exposed printer bar at the front of the machine (see Figure 4-23).

Although the DVD could be read after both high concentration, high RH runs, a loud humming noise was noted at the one-year testing that had not been present at five months. No visual changes were noted for either of these disks, but something must be occurring to the coatings to cause this first indication that the disks are becoming hard to read. The change in coatings also opens up the possibility that at some not-too-distant point, these two DVDs would no longer be functional.

This statement is supported by the fact that the CD could not be read after run R07, the run with the harshest fumigation conditions that included the elevated temperature (27 °C). In the first few months, there were intermittent failures of the CD, and sometimes only certain tracks would play. But at month five and at year's end, the disk could not be read at all. At first there appeared to be no visual indication why this failure was happening, but upon closer inspection, the coating on the disk appeared to have thinned (see Figure 4-22). The thinning coating on the DVDs appears to be causing the humming noise when the DVDs are read. In addition, since the humming noise was not present at five months, but was present at year's end, the damage from the fumigation process to these disks is apparently progressive, possibly due to continued degradation of a protective plastic layer, or progressive damage caused by the act of reading the optical disk through a damaged protective layer.

5.3 Category 4 Equipment

PC-Doctor® Service Center™ 6 is commercially available software designed to diagnose and detect computer component failures. While the exact number and type of tests depends on the system being tested, for the case of the Category 4 equipment a total of 172 tests were run. Some tests were not compatible with Dell™ basic input/output system (BIOS) under Windows and needed to be tested in the disk operating system (DOS) environment. A complete list of the PC-Doctor® Service Center™ 6 tests is shown in Appendix D. The PC-Doctor® Service Center™ 6 protocol was developed and provided by Alcatel-Lucent for this effort. Alcatel-Lucent determined the appropriate choice of the use of PC-Doctor® in order to have an industry-accepted standard method of determining pass versus failure of the computer subsystems. PC-Doctor® Service Center™ 6 functionality testing was conducted pre-fumigation, one day post-fumigation, then monthly for the next year, except for months 9 and 11. This testing provided valuable information about the extent and time dependence of the degradation of these computers following the various ClO_2 exposure scenarios. All computers were kept under ambient laboratory conditions where humidity was not controlled.

Over the course of the experiment, attempts were made to mitigate memory problems. Dual in-line memory module (DIMM) cards were reinserted into some of the computers so that they could recover from memory errors and reboot and attempts were made to resolve dust problems (visible dust was vacuumed out to prevent surface resistance problems due to hygroscopic dust).

In several cases, computers would not reboot after fumigation or occasional shut-downs. A beep code was sometimes heard, indicating a problem with the memory module. In other cases, there was no beep code, but the light emitting diode (LED) combination on the front of the computer also indicated a memory error. In all cases, the problem was repaired by removing the memory module and firmly reinserting it. Pulling out and reseating the DIMM card served the purpose of wiping the corrosion off the contacting surfaces, allowing for a good connection contact. The likelihood of a DIMM failure was proportional to the amount of ClO_2-generated dust present, in turn proportional to ClO_2 concentration and RH during exposure.

The memory module problem seems to have occurred following the longer term complete de-energizing of the motherboard during the PC-Doctor® power supply tests. The memory module problem did not occur during regular reboots or even unplugging of the computers. In March, 2008, the PC-Doctor® testing protocol was changed to remove redundant power supply tests; i.e., if the motherboard had previously passed all tests, it

Table 5-5. DIMM Card Reseating Dates

Decon ID	Fumigation Condition	Dates of Reseating Memory Module
008	75 ppmv ClO_2, 75% RH, On	10/21/2007,1/31/2008
004	3000 ppmv ClO_2, 75% RH, Off	10/09/200, 3/27/2008
013	75 ppmv ClO_2, condensing RH, On	10/09/2007
017	75 ppmv ClO_2, condensing RH, On	10/09/2007
016	3000 ppmv ClO_2, 90% RH, On	10/30/2007,1/07/2008
024	3000 ppmv ClO_2, 90% RH, On	10/30/2007
023	3000 ppmv ClO_2, 75% RH, On	10/09/2007,10/30/2007, 11/26/2007
003	3000 ppmv ClO_2, 75% RH, On	10/09/2007,10/30/2007, 12/30/2007,1/28/2008

was apparent that the motherboard was being powered and the motherboard was not tested independently for power supply. The memory module failures were sharply reduced after this change in protocol, though it is unclear whether this increase in reliability was due to this step or some other uncontrolled effect. Table 5-5 shows the dates when, following PC-Doctor® testing, the DIMM card was reseated. The one date following the change in protocol is shown in red.

Standard protocol called for each test to be performed once. If any particular test failed the first time, the computer was tested a second time to allow for possible human error. A test failed the second time was labeled "Fail". If the test failed the first time but passed the second time, it was labeled "Pass2". For tabulation, a score of 1,000 was assigned to each "Fail", while a "Pass2" received a score of 1. During each pre- and post fumigation testing period, a total PC-Doctor® score was assigned to each computer based upon the number of tests failed on the first or second attempt. Table 5-6 shows this score for each month for each computer. For months and computers where tests received a "Fail", the specific tests that failed are listed by test number for the month in adjacent columns. The test numbers are described in Table 5-6. All yellow-highlighted test numbers are related to DVD drive components, and orange-highlighted test numbers are related to floppy disk drive components.

As an example, Table 5-6 shows DECON014 with a score of 6,000 for October and 5001 for December. These numbers mean that during October testing, 6 specific tests received a "Fail" during testing (6 x 1,000), while during December, 1 test received a "Pass2" (1 x 1) and 5 tests received a "Fail" (5 x 1,000). The column to the right under the appropriate date shows the number of the test that failed. Cross-reference this number with Appendix D to find that, for October, tests 53-58 all test the CD drive. These tests are highlighted yellow. During November testing, only one test, 168, received a "Fail, which is not highlighted because it is a test for PCI connectors, which is neither related to the DVD drive nor the floppy disk drive. On the other hand, all of the "Fails" during April were for the floppy disk drive.

Alcatel-Lucent compiled a table of all subsystem components of the Category 4 computers and related them to PC-Doctor® Service Center™ 6 tests. The list of subsystem components is shown in Appendix C. Table 5-7 shows the correlation between the failed test number and these computer subsystems which could have failed in order to result in the PC-Doctor® failure. For example, the DECON014 October "Fail" for test 53 (from Table 5-6 as discussed above) could have been due to subsystem 18, 57, 58, 59, 60, 61, or 62. These subsystems are identified in the column to the right: DVD drive cable connector, DVD drive motor, DVD drive head, DVD drive power connector, DVD drive power cable, DVD drive data cable, DVD drive drawer open/close button on chassis. Failure of one subsystem (such as the CD/DVD drive) can result in many individual PC-Doctor® test failures.

As the failed tests in Table 5-6 were examined, regardless of fumigation scenario, the vast majority (83.6 percent) were seen to be related to the DVD drive (yellow highlight). Some other failures (4.4 percent) were related to the floppy drive (orange highlight). Almost all other failures – and accounting for no more than 12 percent of the total failures during the year-long testing period – were related to connectors.

Table 5-6. PC-Doctor® Tests That Failed Twice for all Computer Fumigation Scenarios (Yellow = DVD-related components; Orange = Floppy drive-related components)

0 ppmv, 40% RH, On					
decon018				December	May
On		Day	Score	5001	13000
	August	-10	0	54	47
	September	1	0	55	48
	October	30	0	56	49
	November	60	0	57	50
	December	90	5001	58	51
	January	120	0		52
	February	150	0		53
	March	180	0		54
	April	210	0		55
	May	240	13000		56
					57
	July	300	0		58
					70
	September	360	0		

0 ppmv, 90% RH, On

decon009 On-1		Day	Score	January 1000	February 5000	May 5000
	August	-10	0	70	**54**	**54**
	September	1	0		**55**	**55**
	October	30	0		**56**	**56**
	November	60	0		**57**	**57**
	December	90	0		**58**	**58**
	January	120	1000			
	February	150	5000			
	March	180	0			
	April	210	0			
	May	240	5000			
	July	300	0			
	September	360	0			

decon021 On-2		Day	Score	January 8000	February 1000	March 1000	April 12000	May 1000	July 1000
	August	-10	0	**52**	**52**	**52**	**47**	**52**	**52**
	September	1	0	**53**			**48**		
	October	30	0	**54**			**49**		
	November	60	0	**55**			**50**		
	December	90	0	**56**			**51**		
	January	120	8000	**57**			**52**		
	February	150	1000	**58**			**53**		
	March	180	1000	70			**54**		
	April	210	12000				**55**		
	May	240	1000				**56**		
							57		
	July	300	1000				**58**		
	September	360	0						

75 ppmv, 40% RH, On

decon005 On-1		Day	Score	January 7001	February 1000	March 11000	May 1000
	August	-10	0	**53**	**53**	**47**	**52**
	September	1	0	**54**		**48**	
	October	30	0	**55**		**49**	
	November	60	0	**56**		**50**	
	December	90	0	**57**		**51**	
	January	120	7001	**58**		**53**	
	February	150	1000	70		**54**	
	March	180	11000			**55**	
	April	210	0			**56**	
	May	240	1000			**57**	
						58	
	July	300	0				
	September	360	0				

decon007 On-2		Day	Score	October 13000
	August	-10	0	**46**
	September	1	0	**47**
	October	30	13000	**48**
	November	60	0	**49**
	December	90	0	**50**
	January	120	0	**51**
	February	150	0	**52**
	March	180	0	**53**
	April	210	0	**54**
	May	240	1	**55**
				56
	July	300	0	**57**
				58
	September	360	0	

75 ppmv, 75% RH, On

decon008				October	January
On-1		Day	Score	16000	13000
	August	-10	0	**47**	**47**
	September	1	0	**48**	**48**
	October	30	16000	**49**	**49**
	November	60	9	**50**	**50**
	December	90	0	**51**	**51**
	January	120	13000	**52**	**52**
	February	150	1	**53**	**53**
	March	180	0	**54**	**54**
	April	210	0	**55**	**55**
	May	240	0	**56**	**56**
				57	**57**
	July	300	0	**58**	**58**
				89	70
	September	360	0	90	
				91	
				92	

decon019				January
On-1		Day	Score	11000
	August	-10	0	**48**
	September	1	0	**49**
	October	30	0	**50**
	November	60	0	**51**
	December	90	0	**52**
	January	120	11000	**53**
	February	150	0	**54**
	March	180	0	**55**
	April	210	0	**56**
	May	240	0	**57**
				58
	July	300	0	
	September	360	0	

75 ppmv, Condensing, RH-1, -2, and -3

decon013				February	March	April	May	July
RH-1		Day	Score	2000	1000	1000	1001	1000
	August	-10	0	**52**	**52**	**52**	**53**	**52**
	September	1	0	70				
	October	30	0					
	November	60	1					
	December	90	1					
	January	120	1					
	February	150	2000					
	March	180	1000					
	April	210	1000					
	May	240	1001					
	July	300	1000					
	September	360	0					

decon017				October	February	May
RH-2		Day	Score	2000	1000	1001
	August	-10	0	**47**	70	**53**
	September	1	0	100		
	October	30	2000			
	November	60	2			
	December	90	0			
	January	120	0			
	February	150	1000			
	March	180	0			
	April	210	0			
	May	240	1001			
	July	300	0			
	September	360	0			

decon020				October	November	January
RH-3		*Day*	*Score*	1000	1001	13000
	August	-10	0	**58**	**53**	**47**
	September	1	1			**48**
	October	30	1000			**49**
	November	60	1001			**50**
	December	90	0			**51**
	January	120	13000			**52**
	February	150	1			**53**
	March	180	0			**54**
	April	210	0			**55**
	May	240	0			**56**
						57
	July	300	0			**58**
						70
	September	360	0			

3000 ppmv, 75% RH, Off

decon004 Off-1	Day	Score	October 7000	November 7000	December 7001	January 7001	February 7000	March 7000	April 7000	May 7001	July 6000	September 7002
August	-10	1	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**
September	1	0	**53**	**53**	**53**	**53**	**53**	**53**	**53**	**53**	**53**	**53**
October	30	7000	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**
November	60	7000	**55**	**55**	**55**	**55**	**55**	**55**	**55**	**55**	**55**	**55**
December	90	7001	**56**	**56**	**56**	**56**	**56**	**56**	**56**	**56**	**56**	**56**
January	120	7001	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**	**57**
February	150	7000	**58**	**58**	**58**	**58**	**58**	**58**	**58**	**58**		**58**
March	180	7000										
April	210	7000										
May	240	7001										
July	300	6000										
September	360	7002										

decon014 Off-2	Day	Score	October 6000	November 1000	December 5001	January 14000	March 1000	April 5000	May 5002
August	-10	0	**53**	168	**54**	1	**46**	**59**	**54**
September	1	0	**54**		**55**	**46**		**60**	**55**
October	30	6000	**55**		**56**	**47**		**61**	**56**
November	60	1000	**56**		**57**	**48**		**62**	**57**
December	90	5001	**57**		**58**	**49**		**63**	**58**
January	120	14000	**58**			**50**			
February	150	0				**51**			
March	180	1000				**52**			
April	210	5000				**53**			
May	240	5002				**54**			
						55			
July	300	0				**56**			
						57			
September	360	0				**58**			

3000 ppmv, 75% RH, On

decon003 On-1		Day	Score	October 12000	February 14000	April 1000	May 1000
	August	-10	0	**47**	1	**52**	70
	September	1	0	**48**	**46**		
	October	30	12000	**49**	**47**		
	November	60	0	**50**	**48**		
	December	90	1	**51**	**49**		
	January	120	1	**52**	**50**		
	February	150	14000	**53**	**51**		
	March	180	0	**54**	**52**		
	April	210	1000	**55**	**53**		
	May	240	1000	**56**	**54**		
				57	**55**		
	July	300	0	**58**	**56**		
					57		
	September	360	0		**58**		

decon023 On-2		Day	Score	May 2000	July 2002
	August	-10	0	**63**	**59**
	September	1	0	70	**60**
	October	30	0		
	November	60	0		
	December	90	0		
	January	120	2		
	February	150	0		
	March	180	0		
	April	210	0		
	May	240	2000		
	July	300	2002		
	September	360	0		

3000 ppmv, 90% RH, On

decon016 On-1		Day	Score	September 2000	October 9000	November 8000	December 12001	January 13002	February 13000	March 15000	April 13000	May 8000	July 13000	September 7000
	August	-10	0	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**
	September	1	2000	100	**52**	**53**	**53**	**53**	**53**	**48**	**48**	**53**	**48**	**53**
	October	30	9000		**53**	**54**	**54**	**54**	**54**	**49**	**49**	**54**	**49**	**54**
	November	60	8000		**54**	**55**	**55**	**55**	**55**	**50**	**50**	**55**	**50**	**55**
	December	90	12001		**55**	**56**	**56**	**56**	**56**	**51**	**51**	**56**	**51**	**56**
	January	120	13002		**56**	**57**	**57**	**57**	**57**	**52**	**52**	**57**	**52**	**57**
	February	150	13000		**57**	**58**	**58**	**58**	**58**	**53**	**53**	**58**	**53**	**58**
	March	180	15000		**58**	100	**59**	**59**	**59**	**54**	**54**	70	**54**	
	April	210	13000		100		**61**	**60**	**60**	**55**	**55**		**55**	
	May	240	8000				**62**	**61**	**61**	**56**	**56**		**56**	
							63	**62**	**62**	**57**	**57**		**57**	
	July	300	13000				90	**63**	**63**	**58**	**58**		**58**	
								100	100	90	100		100	
	September	360	7000							91				
										92				

decon024				September	October	November	December	January	February	March	April	May	July	September
On-2		*Day*	*Score*	2000	9000	2001	16001	8001	7001	33000	14000	10001	7000	7000
	August	-10	0	**47**	**47**	**47**	**46**	**47**	**47**	**47**	**47**	**47**	**47**	**47**
	September	1	2000	**53**	**53**	79	**47**	**53**	**53**	**48**	**48**	**53**	**53**	**53**
	October	30	9000		**54**		**48**	**54**	**54**	**49**	**49**	**54**	**54**	**54**
	November	60	2001		**55**		**49**	**55**	**55**	**50**	**50**	**55**	**55**	**55**
	December	90	16001		**56**		**50**	**56**	**56**	**51**	**51**	**56**	**56**	**56**
	January	120	8001		**57**		**51**	**57**	**57**	**52**	**52**	**57**	**57**	**57**
	February	150	7001		**58**		**52**	**58**	**58**	**53**	**53**	**58**	**58**	**58**
	March	180	33000		80		**53**	79		**54**	**54**	**62**		
	April	210	14000		100		**54**			**55**	**55**	70		
	May	240	10001				**55**			**56**	**56**	79		
							56			**57**	**57**			
	July	300	7000				**57**			79-100	**58**			
							58				79			
	September	360	7000				79				80			
							80							
							100							

Table 5-7. PC-Doctor® Failed Test Correlation to PC Subsystem Components

Failed PC-Doctor® Test	Subsystems	Description of Subsystem Components
1	none	
46	18, 57-62	DVD drive cable connector, DVD Drive (drive motor, head, power connector, power cable, data cable, drawer open/close on chassis)
47	18, 57-62	
48	18, 57-62	
49	18, 57-62	
50	18, 57-62	
51	18, 57-62	
52	18, 57-62	
53	18, 57-62	
54	18, 57-62	
55	18, 57-62	
56	18, 57-62	
57	18, 57-62	
58	18, 57-62	
59	3, 10, 26, 45-49	IO and SuperIO Controllers (Motherboard), Floppy drive connector, Floppy disc drive (motor, head, power connector, power cable, cable, data cable)
60	3, 10, 26, 45-49	
61	3, 10, 26, 45-49	
62	3, 10, 26, 45-49	
63	3, 10, 26, 45-49	
70	12	LAN-On-Motherboard
79	10, 74	SuperIO Controller (Motherboard), COM1 connector on chassis
80	10, 74, 80	SuperIO Controller (Motherboard), COM1 connector on chassis, USB connector on chassis
81	10, 74	SuperIO Controller (Motherboard), COM1 connector on chassis
82	10, 74	SuperIO Controller (Motherboard), COM1 connector on chassis
83	10, 74	SuperIO Controller (Motherboard), COM1 connector on chassis
84	10, 75	SuperIO Controller (Motherboard), LPT1 connector on chassis
85	10, 75	SuperIO Controller (Motherboard), LPT1 connector on chassis
86	3	IO Controller IC
87	3, 21, 78	IO Controller IC, MthBd cable connector, USB connector on chassis
88	3, 21, 79	IO Controller IC, MthBd cable connector, USB connector on chassis
89	3, 21	IO Controller IC, MthBd cable connector
90	3, 21, 81	IO Controller IC, MthBd cable connector, USB connector on chassis
91	3, 21, 82	IO Controller IC, MthBd cable connector, USB connector on chassis
92	3, 21, 83	IO Controller IC, MthBd cable connector, USB connector on chassis
93	3, 72, 76	IO Controller IC, USB Data Cable, USB connector on chassis
94	3, 70, 77	IO Controller IC, USB Data Cable, USB connector on chassis
95	3, 7	IO Controller IC, Graphic and Memory Controller Hub
96	3, 7	IO Controller IC, Graphic and Memory Controller Hub
97	3, 7, 9	IO Controller IC, Graphic and Memory Controller Hub, SPI (Serial Peripheral Device) Flash Device
98	3, 7, 9	IO Controller IC, Graphic and Memory Controller Hub, SPI (Serial Peripheral Device) Flash Device
99	3	IO Controller IC
100	14, 85, 86	Audio CODEC (comp/decomp), MthBrd; Audio line out and in on chassis
168	24, 25	PCI connectors (2 slots)

Alcatel-Lucent determined that the DVD drive failures were due to damage by the ClO_2 to the optical pick-up assembly.[15] They identified damage to the quarter-wave plate, the objective and focusing lenses, and the 90 turning mirror.

Alcatel-Lucent concluded:

The root cause of failure in the exposed CD/DVD drives is laser and chemical damage of the passive optical components in the optical parametric amplifier, OPA. These optics sit in an optical bench which is entirely open so they experience the full effect of the decontamination gases during exposure. The most heavily damaged optics are those fabricated using optical plastics. Extensive optical damage is observed in these plastics which are used for coatings, substrates, and birefringent materials. The passive optical components in the drive which are fabricated from inorganic materials generally have far less damage.[15]

Several other conclusions can be drawn from the PC-Doctor® results:

- Except for those computers subjected to the very worst conditions, all computer failures were intermittent and all computers passed the suite of PC-Doctor® tests at the final one-year testing. The only exceptions to this observation were for:
  - One of the two computers at 3,000 ppmv ClO_2, 75 percent RH failed tests for DVD components at every post-fumigation test.
  - Both of the computers at 3,000 ppmv ClO_2, 90 percent RH experienced failures every month, most being DVD-related.
- The control computers (no ClO_2 fumigation and at ambient [40 percent] and high [90 percent] RH) also experienced intermittent failures, again with the vast majority being related to the DVD drives.
- Fumigation at 75 ppmv ClO_2 resulted in failures very similar to those seen at ambient conditions. Although there were more PC-Doctor® tests that failed, the failures were primarily associated with the DVD drives and were intermittent in nature.
- Many subsystems are hardy and unaffected by fumigation.

Burn-In Test (BIT) was not run during fumigation exposure. Alcatel-Lucent provided the BIT protocol after some computers had already been exposed. Computers were turned on and allowed to go into stand-by mode according to the preset power mode options. This condition was considered representative of most systems during a fumigation event.

The results of the BIT conducted eight hours a day, 5 days a week, were similar to the PC-Doctor® results and can be summarized as follows:

- Failures were associated with either the CD/DVD or floppy drives, or various connectors (primarily the parallel port, USB plug, and serial port).
- On this more continuous operational basis of 40 hours per week, there was a higher and more frequent failure of the floppy drives than was seen with the monthly PC-Doctor® tests.
- As with the PC-Doctor® tests, failures were intermittent.

Table 5-8 provides a total of all incidents of PC-Doctor® Service Center™ 6 tests that received a "Fail." For each test condition, the results are shown for each of the two computers that underwent year-long testing.

Table 5-8. Total "Fail" Results over Year-Long Study

Temp, °C	**24**	**24**	**24**	**24**	**24**	**24**	**24**
RH	**40%**	**40%**	**75%**	**75%**	**75%**	**90%**	**90%**
ppmv, Computer Power State	**0, On**	**75, On**	**75, On**	**3,000, Off**	**3,000, On**	**0, On**	**3,000, On**
Test Condition	**7**	**6**	**5**	**1**	**2**	**4**	**3**
Computer A	18	20	29	69	28	11	113
Computer B	NA	13	11	37	4	25	115

NA –Not Applicable

6.0 Fumigation Effectiveness and Fumigation Safety

6.1 Fumigation Effectiveness

BIs were used to obtain an indication of the potential impact of local conditions on the effectiveness of the ClO_2 fumigation process to inactivate BA spores potentially located within the computer. Specifically, the BIs were used to investigate ClO_2 sporicidal effectiveness under the different fumigation scenarios for localized hot spots inside the computers, where the RH may be lower because of the heat generated by the computer electronics during operation. The BIs provided a qualitative result of growth or no growth after an incubation period of seven days. BIs have been shown not to correlate directly with achieving target fumigation conditions for BA spores or inactivation of BA spores on common building surfaces.[14] While BIs do not necessary indicate achievement, they provide a sufficient indication of a failure to achieve successful fumigation conditions.[20]

Figures 6-1 and 6-2 show the locations of the BIs within each computer. These locations were chosen based on the available mounting surfaces that afforded relatively unrestricted air flow. Two BIs were placed on the side cover (Figure 6-1) in areas which would remain open once the side panel was closed. Three more BIs (Figure 6-2) were placed inside the computer to capture both high and low air flow locations. BIs were also present in the MEC

Figure 6-1. Location of two of the five BIs inside the computer side cover.

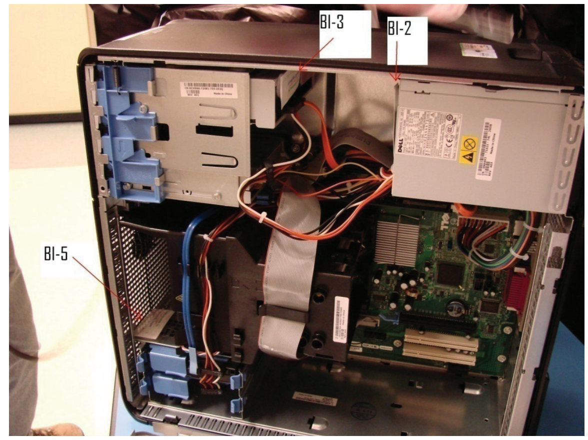


Figure 6-2. Location of the remaining three BIs in both high and low air flow locations inside the computer.

chamber, one on top of each Category 4 computer case and two between the keyboards and monitors on the top shelf of the MEC chamber.

Table 6-1 details the effect of each fumigation scenario on BI viability in both the fumigation chamber and inside the computers. BIs were not placed in the control runs that were conducted without ClO_2.

*Bacillus atrophaeu*s spores are known to be highly sensitive to RH and require a minimum RH of 65 through 75 percent for inactivation with ClO_2. In our 75 ppmv ClO_2, 40 percent RH run, none of the BIs were killed in either the chamber or in any of the individual computers.

Two of the three computers in the 75 ppmv ClO_2, 75 percent run had surviving spores. The three computers that had condensing conditions due to a faulty valve and failed to meet the data quality objectives (DECON013, DECON017 and DECON020) had a 100 percent kill rate.

Of the three 3,000 ppmv ClO_2 runs, the 75 percent RH (in the OFF condition) and the 90 percent RH had a 100 percent kill rate of spores. The 75 percent run (in the ON condition) had spores that remained viable in two of the three computers. The ON condition possibly does create localized areas of higher temperature, and therefore lower humidity, which reduced the effectiveness of the fumigation in this scenario. Although the computers were ON in the 90 percent RH run, the increased bulk chamber humidity may be able to compensate for any elevated temperatures encountered inside the computers.

Table 6-1. BI Viability in the Chamber and Computers for each Fumigation Scenario

Test Condition	Run Name	% Chamber BIs Killed	% Computer BIs Killed
0 ppmv ClO_2, 40% RH	**DECON015** DECON018	NA	NA
75 ppmv ClO_2, 40% RH	DECON005 DECON007 **DECON022**	0	0 0 0
75 ppmv ClO_2, 75% RH	**DECON002** DECON008 DECON019 DECON013 [2] DECON017 [2] DECON020 [2]	100	80 100 20 100 100 100
3,000 ppmv ClO_2, 75% RH (OFF)	DECON004 **DECON006** DECON014	100	100 100 100
3,000 ppmv ClO_2, 75% RH (ON)	DECON003 **DECON012** DECON023	100	80 100 60
0 ppmv ClO_2, 90% RH	DECON009 **DECON010** DECON021	NA	NA
3,000 ppmv ClO_2, 90% RH	**DECON011** DECON016 DECON024	100	100 100 100

Bold – Sent to Alcatel-Lucent
NA – not applicable

6.2 Health and Safety Effects of ClO_2 Fumigation

As discussed in Section 4.3, fumigation with ClO_2 produced large amounts of dust inside the computers, particularly the higher concentration fumigations. When the computers were opened the dust could be seen and an acrid smell (attributed to hydrogen chloride) could be sensed. In addition, even though the dust was vacuumed out during each monthly test, dust continued to be produced for months in those units exposed to the highest ClO_2 concentrations. This dust can be seen clearly in Figure 4-26. Alcatel-Lucent discussed this dust as a potential inhalation health hazard and a possible contact dermatitis hazard in their report (May 2008). The dust also forms an acid when mixed with water.[15]

Vacuuming of the visible dust appears not only to have kept the computers from experiencing the "catastrophic failures" reported by Alcatel-Lucent, but also to have kept all computers almost fully operational after an entire calendar year. Vacuuming also served to remove the majority of this probable health hazard and prevent the dust from being spread outside the computers by the cooling fan or during maintenance and cleaning procedures.

As noted by Alcatel-Lucent:

> *"Copious amounts of corrosion related dust particles were found throughout the interior and exterior of the computers after exposure; wide distribution of particles up and downstream of the cooling fan indicates that this dust readily disperses.[15]"*

Therefore, in any fumigation scenario involving ClO_2, the inside of computers should be vacuumed frequently for as long as required to remove this potential health hazard, as well as to prevent further corrosion or other deleterious effects from this dust. Any other critical equipment that may be susceptible to this corrosion should be examined carefully and treated similarly.

The corrosion formed on only one of two heat sinks inside the computers. This reaction is probably specific to certain alloys of aluminum, the presence of which, in any fumigated equipment or material, could lead to these potential health hazards.

7.0 Quality Assurance

The objective of this study was to assess the impact of ClO_2 on material and electronic equipment due to fumigation with ClO_2 at conditions known to be effective against biological threats. The Data Quality Objectives (DQOs) address this impact using visual inspection (both externally and internally) to assess the loss in value or use of the tested material/equipment, as well as functionality of the material/electronic equipment. The following measurements were considered critical to accomplishing part or all of the project objectives:

- Real-time fumigant concentrations
- Temperature
- RH
- Fumigation time sequence
- Material inspection and electronic equipment functionality time sequence
- Growth/no growth of the BIs.

7.1 Data Quality

The QAPP[22] in place for this testing was followed with few deviations; many of the deviations were documented in the text above. Deviations included out-of-range differences between ClO_2 detection methods, inability to maintain 90 percent RH without condensation, and reducing frequency of visual inspections. These deviations did not substantially affect data quality. Table 7-1 shows actual fumigation parameters and standard deviations for each run. The high standard deviation in RH for Run 8 was caused by the high humidity due to mechanical failure and was the reason this fumigation was omitted from the original matrix. Repeating this run in turn necessitated a reduction of control computers to two.

The evidence of non-homogeneous mixing within the MEC chamber during fumigations (Section 4-3) is disconcerting. Preliminary tests had shown ClO_2 concentration inside a computer to be equal to bulk chamber measurements. BI growth showed no correlation between location and sporicidal effectiveness of fumigation, and internal RH sensors showed no trend of changing RH or temperature with computer location. These data, taken in bulk, suggest that while position within the chamber did have an apparent effect on compatibility, the results are representative of the effects of fumigation of a larger structure.

7.2 Audits

This project was assigned Quality Assurance (QA) Category III and did not require technical systems or performance evaluation audits.

7.3 Data Review

The ARCADIS Work Assignment Leader (WAL), project engineer and QA Officer performed a data review of the detailed IA&E testing performed by Alcatel-Lucent on a subset of the Category 4 computers. The results of their evaluation were detailed in their final report, “Assessment and Evaluation of the Impact of Chlorine Dioxide Gas on Electronic Equipment,” dated May 23, 2008.[15] ARCADIS’ comments and recommendations were summarized in a report to EPA of the same title dated July 31, 2008.

Table 7-1. Data Quality of Fumigation Parameters

Run Number	Concentration (ppmv)	RH	Temperature	Power condition	Computers	Intra-Computer HOBO® RH	Intra-Computer HOBO® Temperature	% Computer BIs killed	% Chamber BIs killed
	(target)	(target)	(target)		#1 (Left)				
	(average)	(average)	(average)		#2 (center)				
	(StDev)	(StDev)	(StDev)		#3 (Right)				
1	3,000	75	24	Off	decon004	80	25	100	100
	3009	77	24		decon006	77	25	100	
	30	0	0		decon014	76	25	100	
2	3,000	75	24	On	decon012	72	24	100	100
	3002	75	24		decon023	83	24	80	
	29	0	0		decon003	79	24	60	
3	3,000	90	24	On	decon024	84	26	100	100
	2922	89	24		decon016	84	26	100	
	42	0	2		decon011	87	26	100	
4	0	90	24	On	decon021	95	26	NA	NA
	0	85	26		decon010	90	27	NA	
	0	1	0		decon009	92	27	NA	
5	75	75	24	On	decon019	75	24	20	100
	71	77	24		decon002	60	27	100	
	2	0	0		decon008	#N/A	#N/A	80	
6	75	40	24	On	decon022	42	25	0	0
	72	41	24		decon005			0	
	5	0	0		decon007	45	25	0	
7	0	40	24	On	decon018	48	23	NA	NA
	0	40	24		decon015	41	22	NA	
	0	1	2		NA	NA	NA	NA	
8	75	75	24	On	decon013	63	25	100	100
	72	70	24		decon017	66	24	100	
	1	21	0		decon020	66	25	100	

8.0 Conclusions

Compatibility of materials and electronic equipment with chlorine dioxide depends on both the concentration of the chlorine dioxide and the RH during exposure.

The most severe effects of fumigation for all three categories of materials were seen at high RH (above 75 percent) and at higher concentrations of ClO_2 (3,000 ppmv ClO_2). Fumigation at 75 ppmv ClO_2 and 40 percent RH does not seem to present any material compatibility issues.

This section summarizes the failures in each category of materials as these failures relate to the functionality of that material/component. By viewing these specific items as surrogates, these experimental results provide insight into which materials and components are most at risk for damage from a decontamination scenario using ClO_2 gas, and how damage to these materials and components could impact operations within a government facility, office or other commercial building immediately after and up to a year after fumigation. These at-risk components can then be sought in any critical equipment, which could include medical devices, airport scanners, and security equipment.

8.1 Category 2 Materials

Category 2 materials included low surface area structural materials expected to have minimal impact on the maintenance of fumigation conditions during the decontamination event; however, their functionality and use may be affected by the fumigation. Copper and aluminum electrical services and electrical breakers suffered increased corrosion on the edges of the electrical boxes in the presence of ClO_2 and RH at 75 percent and above. These effects were only cosmetic – the function of the breakers and services themselves was not compromised. While the wire insulation was sometimes discolored, the wires were always identifiable with the limited palette of colors used for electrical wiring. Multi-stranded data cable may not have all wires identifiable: slight changes in insulation color may require time-intensive mitigation during routine maintenance. The lamp switch suffered intermittent failures at one of two 3,000 ppmv ClO_2 fumigations with RH above 75 percent. The copper coupons were tarnished in the presence of ClO_2 and RH at 75 percent and severely corroded at 3,000 ppmv ClO_2 and condensing humidity. Humidity alone had no effect. ClO_2 compatibility challenges arise for any electrical equipment which has copper contacts. Fumigation of aluminum coupons and the steel receptacle box at RH above 75 percent sometimes created chalky residues on the material. These residues, probably aluminum chloride and zinc chloride, respectively, could be hazardous to human health.

Carbon steel was severely corroded at any ClO_2 exposure in the presence of RH above 40 percent. Carbon steel will naturally rust in the presence of air and moisture, though the short duration of the 90 percent RH test did not show any effects. Note that this carbon steel was not painted or sealed in any way – ClO_2 may be more compatible with painted or sealed carbon steel. Drywall nails and screws were corroded in the presence of ClO_2 and RH at 75 percent or above. The corrosion was not sufficient to affect the function, but this corrosion could cause cosmetic problems. The corrosion could cause functional problems in the longer term (greater than the one year duration of this study). Type 410 stainless steel was severely corroded with 3,000 ppmv ClO_2 at RH above 75 percent. Type 410 stainless steel is typically used for wear-resistant purposes, though its proclivity to corrosion is well known. Type 430 stainless steel was corroded only in one instance of ClO_2 with high humidity. Because Type 430 stainless steel is used mostly for decorative purposes, fumigation of this material is expected to cause at most cosmetic damage. Types 304, 309, and 316 stainless steel seemed compatible with all fumigation conditions.

Inkjet-printed paper exhibited some fading at all conditions, even at 40 percent and 90 percent RH without ClO_2. Increased fading was seen with ClO_2 at RH of 75 percent, and fading sufficiently severe to threaten function was seen at fumigation with RH above 75 percent. Photographs were slightly affected at 75 ppmv ClO_2 and 75 percent RH and severely faded in the presence of higher ClO_2 or higher RH. Laser-printed paper was not affected.

The smoke detector displayed incompatibility at all conditions with RH above 75 percent, even without ClO_2. In the presence of ClO_2 at high RH, however, the battery terminals were sufficiently corroded that the smoke detector would not function. This effect on the battery terminals has been seen in other apparatus as well (e.g., HOBO® RH data loggers). Any device with unsealed batteries, especially any safety device, should be considered incompatible with ClO_2 at an RH above 75 percent.

Table 8-1 shows a summary of effects of fumigation conditions on Category 2 materials.

Table 8-1. Summary of Category 2 Incompatibility with Fumigation Conditions

Temp, °C	**24**	**24**	**24**	**24**	**24**	**24**	**27**
RH	**40%**	**40%**	**75%**	**75%**	**90%**	**90%**	**88%**
ppmv	**0**	**75**	**75**	**3,000**	**0**	**3,000**	**3,000**
Test Condition	**R05**	**R04**	**R03**	**R01**	**R08**	**R06**	**R07**
Cu and Al Services			Corrosion on edges	Corrosion on edges, mild Al service wire discoloration		Corrosion on edges, Al service wire discoloration	Corrosion on edges, Al service wire discoloration
Circuit breakers	Very mild screw corrosion	Very mild screw corrosion	Mild screw corrosion	Mild screw corrosion	Mild screw corrosion	Screw corrosion	Screw corrosion
101 Copper coupons			Tarnish	Tarnish		**Severe Corrosion**	**Severe Corrosion**
Low carbon steel coupons			**Severe corrosion**	**Severe corrosion**		**Severe corrosion**	**Severe corrosion**
410 Stainless steel coupons						**Severe corrosion**	**Severe corrosion**
430 Stainless steel coupons							Corrosion
3003 Aluminum coupons							Chalky residue
Housing insulation.							Discoloration
DSL connector						Discoloration	Discoloration
Steel outlet/ switch box						Chalky residue	
Inkjet paper	Very mild fading	Very mild fading	Moderate fading	Moderate fading	Very mild fading	**Severe fading**	**Severe fading**
Photographs			Slight yellowing	**Severe Fading**		**Severe Fading**	**Severe Fading**
Drywall nails			Mild corrosion	Mild corrosion		Corrosion	Corrosion
Drywall screws			Mild corrosion	Mild corrosion		Corrosion	Corrosion
Stranded wire			Tarnished wire ends	Tarnished wire ends		Corrosion	Corrosion
Smoke detector					Intermittent failure	Intermittent failure	Intermittent failure
Caulk			Intermittent failure				
Lamp (switch)							Intermittent failure

8.2 Category 3 Materials

Category 3 materials included small, personal electronic equipment. Perhaps counter-intuitively, the PDA was completely compatible with all fumigation conditions, possibly because the PDA is relatively sealed against dust and dirt, which also provides some protection against fumigation. All incompatibility issues for this group occurred in the fumigation at 3,000 ppmv ClO_2 and RH above 75 percent (see Table 8-2 and Table 8-3). Cell phones suffered a discolored screen and intermittent button failures after fumigation, although these failures mitigated themselves over time. The corrosion of the roller bar on the fax machine prevented the "send" operation, an example of how a single material incompatibility, i.e., the steel on the roller bar, can cause issues for a more complex item. The DVD and the CD were damaged, though the CD only exhibited failures in one of two instances of this fumigation at 3,000 ppmv ClO_2 and RH above 75 percent. The loud humming noise of the DVD indicates that though damage occurred, the error-correcting algorithms in the DVD player were able to counteract the damage. The damage to the CD was too severe for similar algorithms to retrieve the data. Both results suggest that unsealed data storage could be severely compromised following fumigation at RH above 75 percent. This failure has greater implications than portable storage media as these same optical plastic coatings may be a vital component of many types of security equipment as well.

Table 8-2. Summary of Fumigation Effects on Category 3 Materials

Temp, °C	24	24	24	24	24	24	27
RH	40%	40%	75%	75%	90%	90%	88%
ppmv	0	75	75	3,000	0	3,000	3,000
Test Condition	R05	R04	R03	R01	R08	R06	R07
Cell Phone	---	---	---	Mild Discoloration	---	Discolored/ faded screen, intermittent failure	Discolored/ faded screen, intermittent failure
Fax	---	---	---	---	---	**Severe printer bar corrosion,** **Intermittent send noise**	**Severe printer bar corrosion,** **Send failure and send noise**
DVD	---	---	---	---	---	Loud humming noise	Loud humming noise
CD	---	---	---	---	---	---	Thinned coating, failure reading disk

8.3 Category 4 Equipment

Category 4 materials included desktop computers and monitors. Category 4 equipment exhibited more frequent PC-Doctor® Service Center™ 6 failures after fumigation at 3,000 ppmv ClO_2 and 90 percent RH. The results for computers exposed to 3,000 ppmv ClO_2 and 75 percent RH were notably better for those computers that were "ON" though the fumigation was not as effective at killing the BIs when the computers were "ON". The failure rate for fumigation at standard conditions was slightly elevated for "OFF" computers.

Many of the computer subsystems held up well to fumigations, including, importantly, the hard drive and the motherboard. Many of the significant issues were caused by the hygroscopic dust, which may be specific to few alloys. Removal of this dust through vacuuming and drying of the dust (over time in a relatively dry office atmosphere) ameliorated effects. Significant failures included the DVD drive and floppy drive, lending credence to effects of fumigation on optical plastics. Despite these effects and visible corrosion, the computers, with the exception of some DVD drives, were still in operation with no replacement parts one year after fumigation.

Table 8-3. Total Number of PC-Doctor® Service Center™ 6 "Fail" Results for Year-long Study

Temp, °C	24	24	24	24	24	24	24
RH	40%	40%	75%	75%	75%	90%	90%
ppmv, Computer Power State	0, On	75, On	75, On	3,000, Off	3,000, On	0, On	3,000, On
Test Condition	7	6	5	1	2	4	3
Computer A	**18**	**20**	29	69	28	**11**	113
Computer B	**NA**	**13**	**11**	37	**4**	25	115

NA – not applicable

9.0 Recommendations

This section provides recommendations deduced from the experiments. The recommendations relate to functional failures of various tested materials and electronic components that were subjected to decontamination scenarios using ClO_2 gas. These recommendations are presented below.

9.1 Corrective Actions

Corrective actions can be implemented immediately after the fumigation event to reduce/prevent further degradation of sensitive materials and components. These corrective actions include making copies of all sensitive documents and electronic records as if they were going to be altered, and removing all dust resulting from the fumigation and treating the dust as a health hazard and probable vehicle for further degradation of material and equipment operability.

9.2 Listing of “At Risk” Material and Electronic Components

During the planning stages of a remediation, inventory at-risk components, including those that contain affected subsystems, such as optical plastics. These components could be candidates for alternative decontamination techniques or immediate replacement after fumigation.

9.3 Further Research

Develop a research plan to investigate additional materials/electronic component compatibilities that are vital to other high-end electronic equipment, but not covered under these experiments. The list may include the compatibility of lubricated metals, aluminum alloys, and other types of plastic used in the electronics industry. As more information becomes available on the effectiveness of additional fumigation conditions, investigation of these additional fumigation conditions is important. In planning activities for remediation, the inventory of at-risk items and components can be done so that these items and components can be identified for special alternative decontamination procedures or immediate replacement.

10.0
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Appendix A
Computer Specifications

Base Unit	Dell™ OptiPlex™ 745 Minitower, Intel® Core™ 2 Duo E6400/2.13GHz, 2M, 1066FSB (222-5690)
Processor	NTFS File System, Factory Install (420-3699)
Memory	512MB, Non-ECC, 667MHz DDR2 1x512, Dell™ OptiPlex™ 745 (311-5037)
Keyboard	Dell™ USB Keyboard, No Hot Keys, English, Black, OptiPlex™ (310-8010)
Monitor	Dell™ E157FP,15 Inch Flat Panel15.0 Inch Viewable Image Size, OptiPlex™ and Latitude™ (320-4962)
Video Card	Integrated Video, Intel® GMA3000, Dell™ OptiPlex™ 745 (320-5169)
Hard Drive	80GB SATA 3.0Gb/s and 8MB Data Burst Cache™, Dell™ OptiPlex™ 320 and 745 (341-4214)
Floppy Disk Drive	3.5 inch,1.44MB,Floppy Drive Dell™ OptiPlex™ 320 and 745 Desktop or Minitower (341-3840)
Operating System	Microsoft Windows® XP Professional Service Pack 2, with Media, Dell™ OptiPlex™ 320, 740 and 745 English, Factory Install (420-6287)
Mouse	Dell™ USB 2-Button Entry Mouse with Scroll, Black, OptiPlex™ (310-8008)
TBU	RoHS Compliant Lead Free Chassis and Motherboard, Dell™ OptiPlex™ (464-1131)
CD-ROM or DVD-ROM Drive	16X DVD+/-RW SATA, Black, Roxio Creator™ Dell™ Edition, Dell™ OptiPlex™ 745 Desktop or Minitower (313-4378)
Speakers	No Speaker, Dell™ OptiPlex™ (313-1416)
Documentation Diskette	Resource CD contains Diagnostics and Drivers for Dell™ OptiPlex™ Systems (313-7168)
Factory Installed Software	Energy Smart, Energy Star Labeling, EIST for Dell™ OptiPlex™ (if applicable) (310-8344)
Service	Non-Standard Service Option (900-9006)
Service	Type 6 Contract -Next Business Day Parts Delivery, Initial Year (980-4740)
Service	Dell™ Hardware Warranty, Initial Year (985-2477)
Service	Dell™ Hardware Warranty, Extended Year(s) (985-2478)
Service	Type 6 Contract -Next Business Day Parts Delivery, 2YR Extended (970-8672)
Installation	Standard On-Site Installation Declined (900-9987)
Service One	Dell™ Federal KYHD Service (980-3067)

Appendix B
Parts List of Copper and Aluminum Service Panels

C.E.S. (Garner)
214-A Garner Business Court,
Garner NC, 27529.

Phone: 919-661-1155
Fax: 919-661-8866
Email: Garner0015@ces-us.net

PACKING SLIP

GAR/031103

Date: 01 Oct 2008

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Entered by: Robert Carr

Account: 00150396001

Order Number: EPA

ARCADIS US INC
4915 PROSPECTUS DR
SUITE F
DURHAM NC
27713

Qty	Item	Description	$ Price Per	$ Goods
84	BR110	SP 10A BR BREAKER	5.27 E	442.68 *
1	SHIPPING & HANDLING	SHIPPING & HANDLING	82.15 E	82.15 *
14	P&S PS5266-X	15A 125V PLUG	6.86 E	96.04
100	SO-14/3	SO-14/3	936.02 M	93.60
14	MADISON MCG-50A560	1/2 CORD CONN	449.00 C	62.86
14	C-H BR24L70FGP	70A MLO FL LD CTR	26.00 E	364.00
100	MADISON L-51	3/8 2SCR NMC CONN	25.30 C	25.30
30	NM-B-14/2 ALUM	14/2 ALUM ROMEX	500.00 M	15.00
250	NM-B-14/2-CU-250C	NM-B-14/2-CU-WG-250CL	215.00 M	53.75
14	RACO 192	4SQ 1-1/2D BOX COMB KO	94.50 C	13.23
7	P&S 3232-I	DPLX RCPT-NEMA5-15R	55.00 C	3.85
7	P&S 660-IG	SP 15A120V GRD AC SW	74.50 C	5.22
14	MADISON CPB-50	1/2 PLSTC INS BUSH	12.86 C	1.80
14	P&S TPJ18-I	IV 2G TOG/DPLX PLT	66.07 C	9.25
14	RACO 778	4-IN SQ 1/2D 2G SW RING	183.74 C	25.72

Goods Total: $1294.45
Tax Total: $87.38
Total: $1381.83

Signature: ____________________ Print Name: ____________________

THE RISK IN THE GOODS SHALL PASS TO THE BUYER ON DELIVERY, BUT THE GOODS REMAIN THE PROPERTY OF THE SELLER UNTIL PAID FOR.
GOODS ARE SOLD ACCORDING TO VENDORS AND OUR OWN CONDITIONS OF SALE, COPIES OF WHICH ARE AVAILABLE UPON REQUEST.

E&OE DM/01

Appendix C
Category 4 Subsystems
(Provided by Alcatel-Lucent)

#	Major subsystem	Description	Chipsets involved	PC-Doctor® Tests this subsystem (yes/no)
1	Motherboard	Dual processor CPU chip	Intel® Core™ 2 Duo E6400	y
2	Motherboard	Dual processor CPU heat sink	Intel® Core™ 2 Duo E6400	y
3	Motherboard	IO Controller IC	Intel® 82801HB/82801HR ICH8	y
4	Motherboard	CMOS (CMOS RAM with RTC & NVRAM)	Intel® 82801HB/82801HR ICH8	y
5	Motherboard	SDRAM memory cards (DIMM)	Hyundai 512 MB DDRW-SDRAM	y
6	Mthbd card connector	SRAM DIMM module board mounted connector		y
7	Motherboard	Graphics and Memory Controller Hub	Intel® 82Q965	y
8	Motherboard	Intel 82Q965 heat sink	Intel® 82Q966	y
9	Motherboard	SPI (Serial Peripheral Interface) Flash Device: ROM BIOS FWH (firmware hub) : contains BIOS Setup program POST, PCI auto-config and Plug&Play support	MXIC MX25L8005	y
10	Motherboard	SuperIO Controller (contains floppy drive controller, serial port controller, parallel port controller, power management (fan) controller	SMSC SCH5514D-NS	y
11	Motherboard	LPC Interface TPM (Trusted Platform Module) protects signature keys and encryption		n
12	Motherboard	Lan-On-Motherboard (NIC) with 10/100/GbE support	Broadcom BCM5754KM Ethernet NIC and ATMEL AT45DB001B Flash SPI memory device	y
13	Motherboard	Battery (3V Lithium)	Panasonic CR2032 3V	y
14	Motherboard	Audio CODEC (compression/ decompression)	Analog Devices HO Audio SoundMAX CODEC AD1983	y
15	Motherboard	Frequency timing generator/Real time clock	Intel® Core 2 Duo E6400, ICS9LP5052 and 32.768k crystal clock chip	y
16	Motherboard	battery -- mount and socket		n
17	MthBd cable connector	SATA Drive0 (hard drive)	Intel® 82801HB/82801HR ICH8	y
18	MthBd cable connector	SATA Drive1 (DVD drive)	Intel® 82801HB/82801HR ICH8	y
19	MthBd cable connector	SATA Drive4 (not connected)	Intel® 82801HB/82801HR ICH8	n
20	MthBd cable connector	SATA Drive5 (not connected)	Intel®82801HB/82801HR ICH8	n

#	Major subsystem	Description	Chipsets involved	PC-Doctor® Tests this subsystem (yes/no)
21	MthBd cable connector	Front Panel Connector (ON/OFF switch, 2 USB ports, front audio in/out ports)		y
22	MthBd card connector	PCI Expressx16 connector (SLOT1) (not connected)		n
23	MthBd card connector	PCI Expressx16 connector (SLOT4) (not connected)		n
24	MthBd card connector	PCI Connector (SLOT2)		y
25	MthBd card connector	PCI Connector (SLOT3)		y
26	MthBd cable connector	Floppy drive connector		y
27	MthBd cable connector	Serial connector (not connected)		n
28	MthBd cable connector	Fan connector		n
29	MthBd cable connector	Internal Speaker connector (not connected)		n
30	MthBd cable connector	Processor power connector (4 pin)		y
31	MthBd cable connector	Main power connector (24 pin)		y
32	MthBd component	Beep speaker		n
33	MthBd component	Capacitor		n
34	MthBd component	Resistor		n
35	MthBd component	Transistor		n
36	MthBd component	Choke		n
37	MthBd component	Solder bond pad -- specify location		n
38	MthBd component	screws and other mounting hardware		n
39	Fan	Main chassis fan		n
40	Power supply module	Electrical function		y
41	Power supply module	Mains power plugs (110V)		n
42	Power supply module	Chassis		n
43	Power supply cable to motherbrd 24 pin conn	Power cable		y
44	Floppy disk drive	Chassis		n
45	Floppy disk drive	Motor		y

#	Major subsystem	Description	Chipsets involved	PC-Doctor® Tests this subsystem (yes/no)
46	Floppy disk drive	Head		y
47	Floppy disk drive	Power connector		y
48	Floppy disk drive	Power cable		y
49	Floppy disk drive	Data cable		y
50	Hard drive	Chassis		n
51	Hard drive	Motor		y
52	Hard drive	Head		y
53	Hard drive	Power connector		y
54	Hard drive	Power cable		y
55	Hard drive	Data cable		y
56	DVD Drive	Chassis		n
57	DVD Drive	Drive motor		y
58	DVD Drive	Head		y
59	DVD Drive	Power connector		y
60	DVD Drive	Power cable		y
61	DVD Drive	Data cable		y
62	DVD Drive	Drawer open/close on chassis		y
63	Monitor	Screen		y
64	Monitor	Data Cable		y
65	Monitor	Data Cable connector		y
66	Monitor	Power Cable		y
67	Monitor	Power Cable 110V plug		y
68	Monitor	Video connector on chassis		y
69	Monitor	Base of monitor stand		n
70	Mouse	USB Data Cable		y
71	Mouse	Mechanical operation		y
72	Keyboard	USB Data Cable		y
73	Keyboard	Mechanical operation		y
74	Commun. Port COM1	COM1 connector on chassis		y
75	Printer Port LPT1	LPT1 connector on chassis		y
76	USB Port 1 keyboard	USB connector on chassis		y
77	USB Port 2 mouse	USB connector on chassis		y
78	USB Port 1	USB connector on chassis		y
79	USB Port 2	USB connector on chassis		y
80	USB Port 3	USB connector on chassis		y
81	USB Port 4	USB connector on chassis		y
82	USB Port 5	USB connector on chassis		y

#	Major subsystem	Description	Chipsets involved	PC-Doctor® Tests this subsystem (yes/no)
83	USB Port 6	USB connector on chassis		y
84	Network (LAN) Port	Network (LAN) adapter connector on chassis		y
85	Audio out	Audio line out connector (green) on chassis		y
86	Audio in	Audio line in connector (blue & pink) on chassis		y
87	CASE	Removable side of case		n
88	CASE	Case interior floor		n
89	CASE	Case back panel screens		n
90	CASE	Case front panel		n
91	CASE	PCI Plates		n
92	CASE	Release Latch		n
93	CASE	Screws on exterior		n

Appendix D
PC-Doctor® Service Center™ 6 Tests

Test #	Test
System Board	
1	**RTC Rollover Test**
2	**RTC Accuracy Test**
Intel® Core™ 2 CPU 6400 @ 2.13GHz CPU:0	
3	**Register Test**
4	**Level 2 Cache Test**
5	**Math Register Test**
6	**MMX Test**
7	**SSE Test**
8	**SSE2 Test**
9	**SSE3 Test**
10	**SSSE3 Test**
11	**Stress Test**
12	**Multicore Test**
Intel® Core™ 2 CPU 6400 @ 2.13GHz CPU:1	
13	**Register Test**
14	**Level 2 Cache Test**
15	**Math Register Test**
16	**MMX Test**
17	**SSE Test**
18	**SSE2 Test**
19	**SSE3 Test**
20	**SSSE3 Test**
21	**Stress Test**
22	**Multicore Test**
CMOS	
23	**Checksum Test**
24	**Pattern Test**
512 MB DDR2-SDRAM (666 MHz)	
25	**Pattern Test**
26	**Advanced Pattern Test**
27	**Bit Low Test**
28	**Bit High Test**
29	**Nibble Move Test**
30	**Checkerboard Test**
31	**Walking One Left Test**

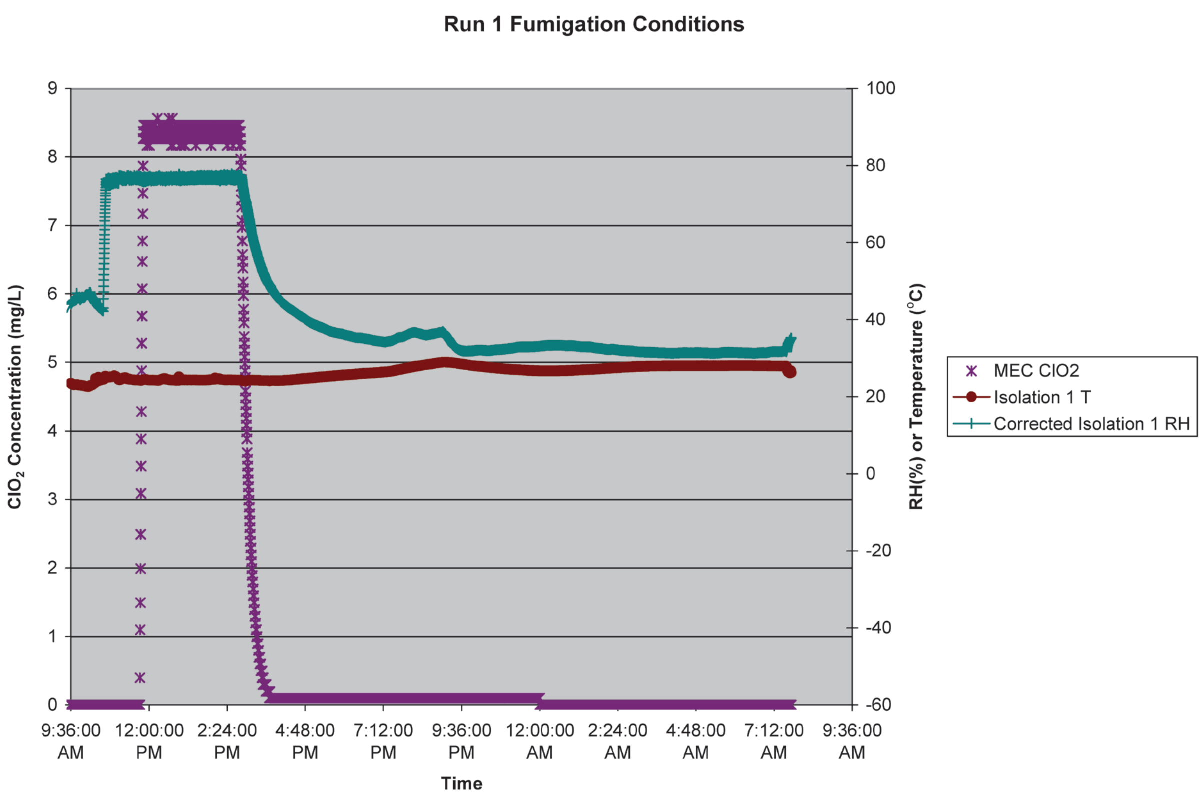
32	**Walking One Right Test**
33	**Auxiliary Pattern Test**
34	**Address Test**
35	**Modulo20 Test**
36	**Moving Inversion Test**
C:	
37	**Linear Seek Test**
38	**Random Seek Test**
39	**Funnel Seek Test**
40	**Surface Scan Test**
41	**SMART Status Test**
42	**SMART Short Self Test**
43	**SMART Extended Self Test**
44	**SMART Conveyance Self Test**
HL-DT-ST DVD+-RW GSA-H31N	
45	**(DVD-RW Drive) Read Write Test**
46	**(DVD-R Drive) Read Write Test**
47	**(CD-R Drive) Read Write Test**
48	**(DVD Drive) Linear Seek Test**
49	**(DVD Drive) Random Seek Test**
50	**(DVD Drive) Funnel Seek Test**
51	**(DVD Drive) Linear Read Compare Test**
52	**(DVD+R DL Drive) Read Write Test**
53	**(DVD+RW Drive) Read Write Test**
54	**(DVD+R Drive) Read Write Test**
56	**(CD-RW Drive) Read Write Test**
57	**CD-ROM Drive) Linear Seek Test**
58	**(CD-ROM Drive) Random Seek Test**
59	**(CD-ROM Drive) Funnel Seek Test**
60	**(CD-ROM Drive) Linear Read Compare Test**
61	**(CD-ROM Drive) CD Audio Test**
Floppy disk drive	
62	**Linear Seek Test**
63	**Random Seek Test**
64	**Funnel Seek Test**
65	**Surface Scan Test**
PC-Doctor® USB Test Key 2.0 USB Device	
66	**Scan Test Port 1**
67	**Scan Test Port 2**
68	**Scan Test Port 3**
69	**Scan Test Port 4**
70	**Scan Test Port 5**
71	**Scan Test Port 6**

Intel® Q965/Q963 Express Chipset Family	
72	**Primary Surface Test**
73	**Fixed Transformation and Lighting Test**
74	**Transformation and Lighting Stress Test**
Intel® Q965/Q963 Express Chipset Family	
75	**Primary Surface Test**
76	**Fixed Transformation and Lighting Test**
77	**Transformation and Lighting Stress Test**
Broadcom NetXtreme 57xx Gigabit Controller	
78	**Network Link Test**
79	**TCP/IP Internal Loopback Test**
80	**Network External Loopback Test**
HID Keyboard Device	
81	**Keyboard Interactive Test**
Dell™ USB Mouse	
82	**Mouse Interactive Test**
SoundMAX Integrated Digital HD Audio Driver	
83	**Playback Mixer State Test**
84	**Sound Interactive Test**
Intel® Q965/Q963 Express Chipset Family	
85	**Audio Visual Interleave (AVI) Interactive Test**
Dell ™ E157FP (Plug and Play Monitor)	
86	**Monitor Interactive Test**
Communications Port (COM1)	
87	**External Register Test**
88	**External Loopback Test**
89	**Internal Register Test**
90	**Internal Control Signals Test**
91	**Internal Send and Receive Test**
ECP Printer Port (LPT1)	
92	**Internal Read and Write Test**
93	**External Read and Write Test**
PCI Bus	
94	**Configuration Test**
PC-Doctor® USB Test Key 2.0 USB Device	
95	**USB Status Test**
Dell™ USB Keyboard	
96	**USB Status Test**
Dell™ USB Mouse	
97	**USB Status Test**
Intel® Q963/Q965 PCI Express Root Port – 2991	
98	**PCI Express Status Test**
Microsoft UAA Bus Driver for High Definition Audio	

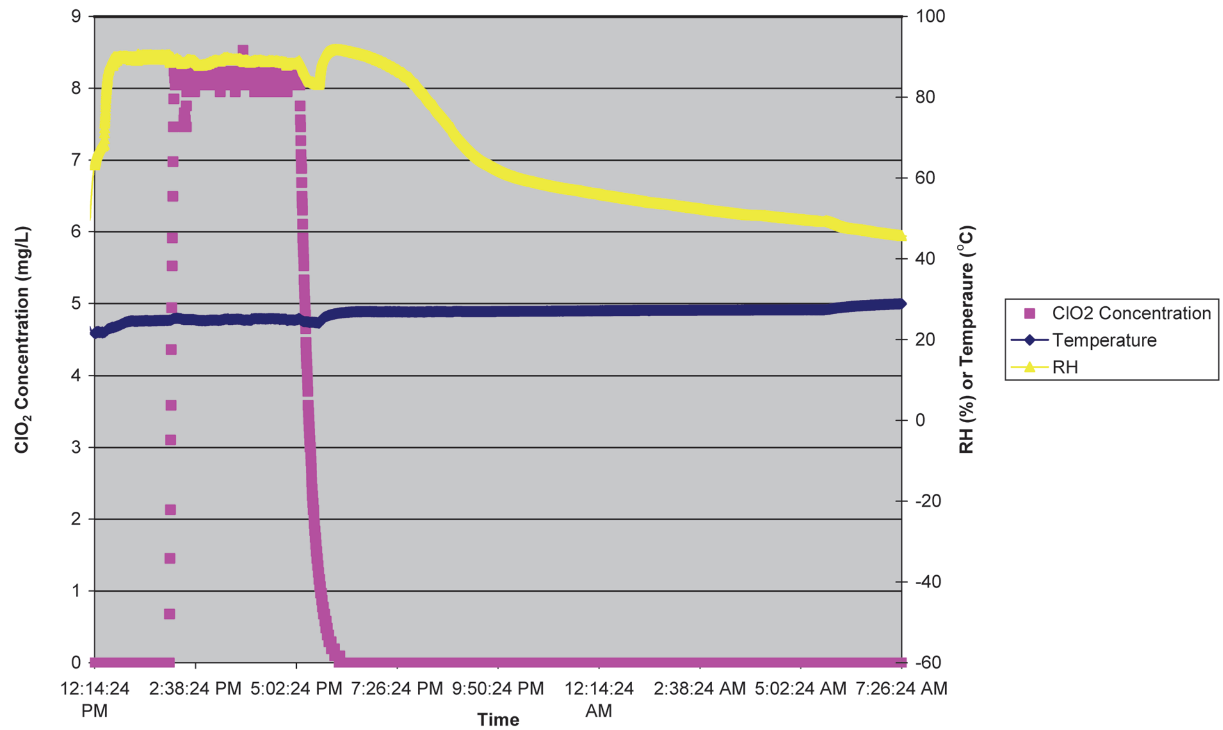
99	**PCI Express Status Test**
Intel® ICH8 Family PCI Express Root Port 1 - 283F	
100	**PCI Express Status Test**
Intel® ICH8 Family PCI Express Root Port 5 - 2847	
101	**PCI Express Status Test**
Broadcom NetXtreme 57xx Gigabit Controller	
102	**PCI Express Status Test**
SoundMAX Integrated Digital HD Audio Driver	
103	**Rough Audio Test**
Batch 5	
104	System Timer
105	BIOS Timer
106	IRQ Controller
107	DMA Channels
108	RAM Refresh
109	RTC Clock
110	CMOS RAM
111	Keyboard
112	PCI
113	USB Port
114	Video Memory
115	Video Pages
116	VGA Controller Registers
117	VGA Color-DAC Registers
118	VESA Full Video Memory Test
119	COM 1 Registers And Interrupts
120	COM 1 Internal Loopback
121	COM 1 FIFO Buffers (16550A)
122	LPT 1 Command And Data Port
123	SMBUS
Batch 4	
124	CPU 1 CPU Registers
125	CPU 1 CPU Arithmetics
126	CPU 1 CPU Logical Operations
127	CPU 1 CPU String Operations
128	CPU 1 CPU Misc Operations
129	CPU 1 CPU Interrupts/Exceptions
130	CPU 1 CPU Buffers/Cache
131	CPU 1 CoProc Registers
132	CPU 1 CoProc Commands
133	CPU 1 CoProc Arithmetics
134	CPU 1 CoProc Transcendental
135	CPU 1 CoProc Exceptions

136	CPU 1 MMX Test
137	CPU 2 CPU Registers
138	CPU 2 CPU Arithmetics
139	CPU 2 CPU Logical Operations
140	CPU 2 CPU String Operations
141	CPU 2 CPU Misc Operations
142	CPU 2 CPU Interrupts/Exceptions
143	CPU 2 CPU Buffers/Cache
144	CPU 2 CoProc Registers
145	CPU 2 CoProc Commands
146	CPU 2 CoProc Arithmetics
147	CPU 2 CoProc Transcendental
148	CPU 2 CoProc Exceptions
149	CPU 2 MMX Test
150	Base Fast Pattern
151	Base Fast Address
152	Base Medium Pattern
153	Base Medium Address
154	Base Heavy Pattern
155	Base Heavy Address
156	Base Bus Throughput
157	Extended Fast Pattern
158	Extended Fast Address
159	Extended Medium Pattern
160	Extended Medium Address
161	Extended Heavy Pattern
162	Extended Heavy Address
163	Extended Code Test
164	Extended Advanced Pattern
PCI post Card Test	
165	D1
166	D2
167	D3
168	D4
169	D5
170	D6
Power Supply Tests	
171	20/24
172	Motherboard
173	Hard drive
174	DVD drive
175	Floppy Drive

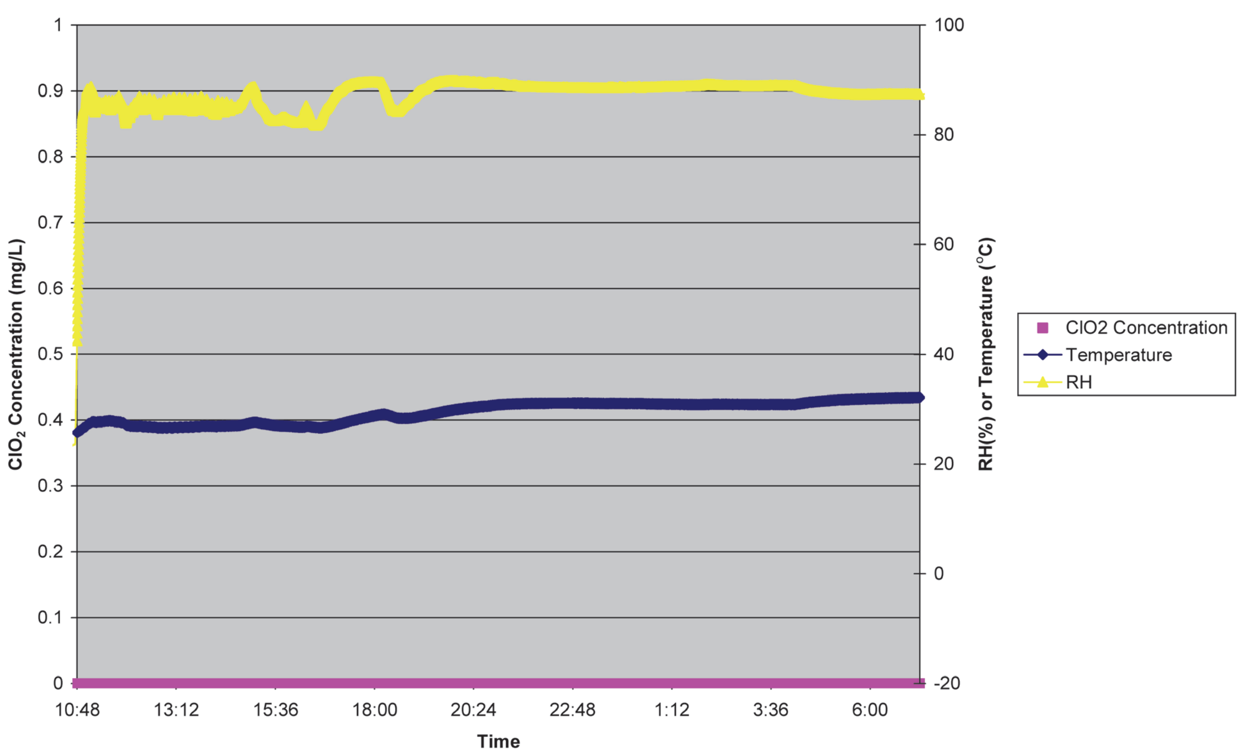
Appendix E
Exposure Conditions



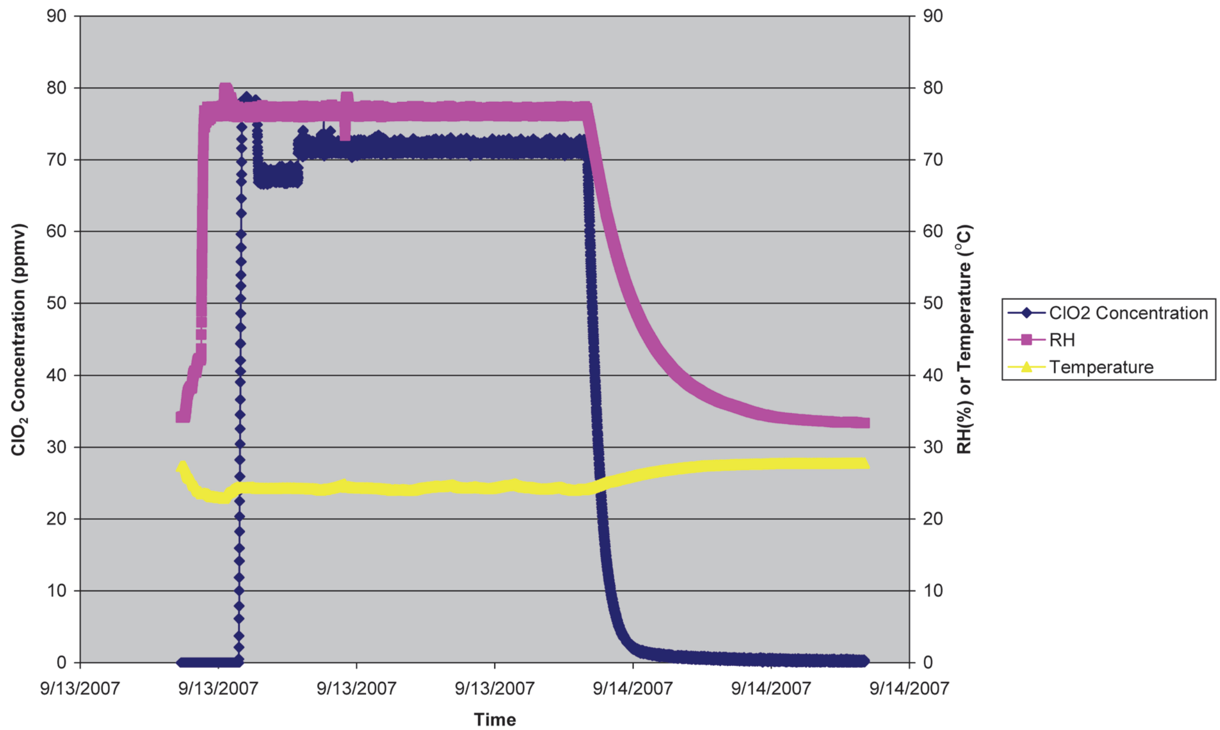
Run 3 Fumigation Conditions



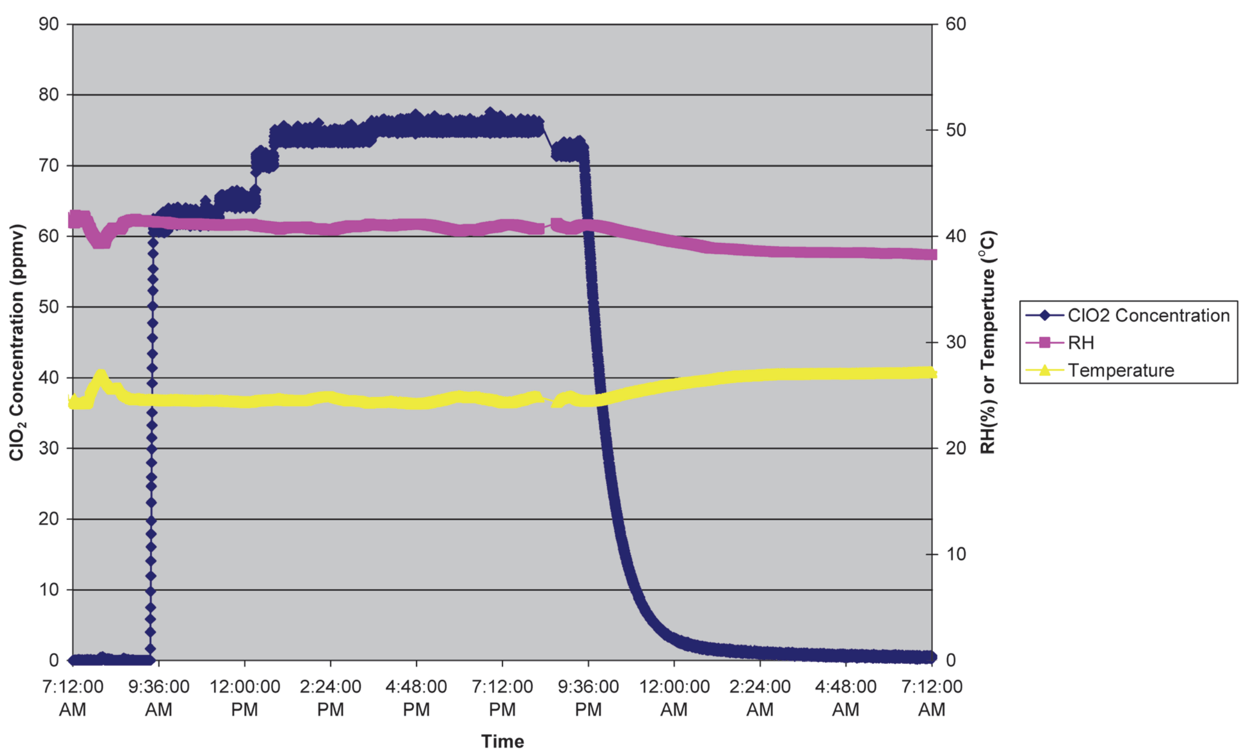
Run 4 Fumigation Conditions

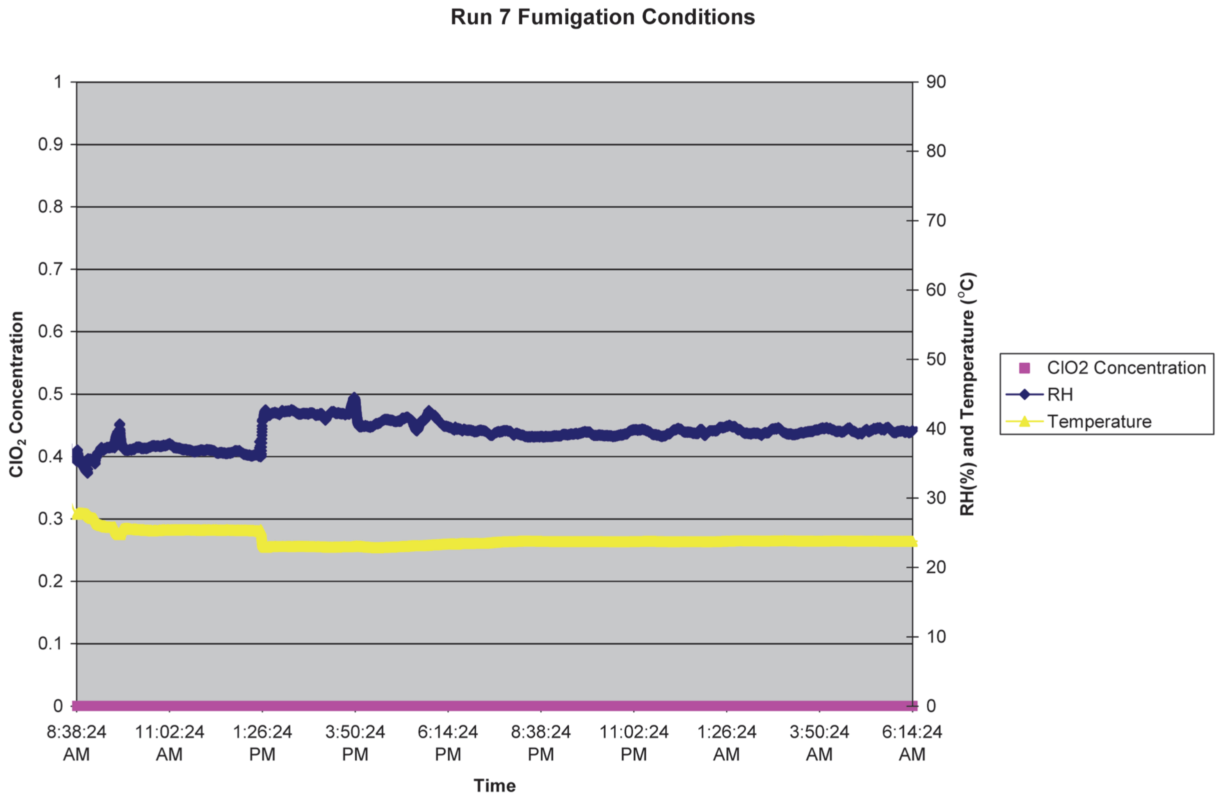


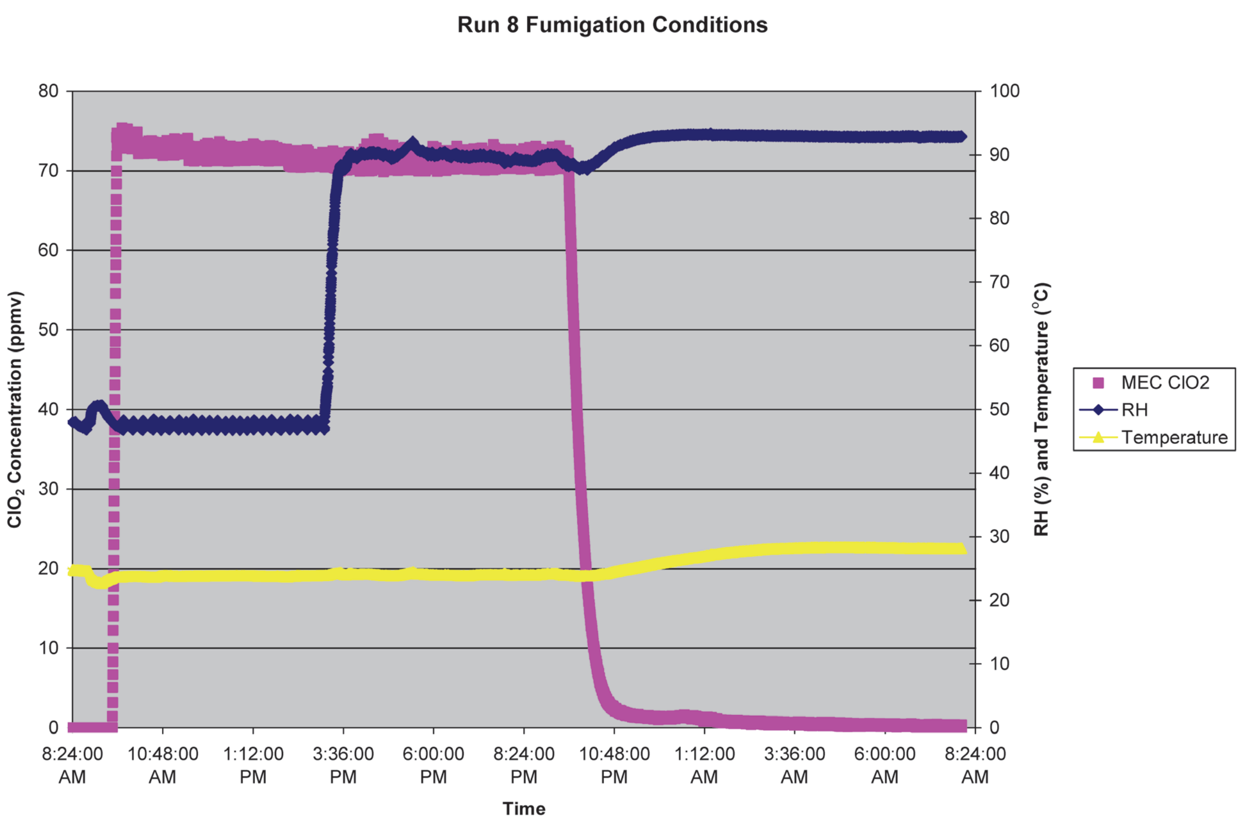
Run 5 Fumigation Conditions



Run 6 Fumigation Conditions




Run 7 Fumigation Conditions
ClO2 Concentration
RH(%) and Temperature (°C)
Time
ClO2 Concentration
RH
Temperature
8:38:24 AM
11:02:24 AM
1:26:24 PM
3:50:24 PM
6:14:24 PM
8:38:24 PM
11:02:24 PM
1:26:24 AM
3:50:24 AM
6:14:24 AM


Run 8 Fumigation Conditions
ClO2 Concentration (ppmv)
RH (%) and Temperature (°C)
Time
MEC ClO2
RH
Temperature
8:24:00 AM
10:48:00 AM
1:12:00 PM
3:36:00 PM
6:00:00 PM
8:24:00 PM
10:48:00 PM
1:12:00 AM
3:36:00 AM
6:00:00 AM
8:24:00 AM

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