

HYDROXYL RADICALS FOR FIRE RESTORATION: Do They Work? Are They Safe?

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Project GC15-13455

In conjunction with
Odorox Hydroxyl Group
October 2015

1.0 Abstract

This is Part Two of a Wonder Makers Environmental restoration industry project to evaluate the safety of post-fire environments and the potential risk to restoration contractors and others present in these environments, as well as the effect that Odorox hydroxyl generators may have with respect to the safety of these environments. In Part One, after an extensive evaluation of existing literature conducted by Wonder Makers, it was determined that there are potential risks due to the uncertainty of the types and quantities of volatile organic compounds (VOCs) present after a fire. This Part Two report explains the methodology and results of an experiment done to assist the restoration industry in determining the effect of hydroxyl radicals when used as part of fire restoration.

The study involved the construction of a small room finished to represent a standard residential or commercial environment. A controlled fire was ignited in the test room and fed with standard household components such as Romex wire, painted drywall, plastic switch plates, Styrofoam, etc. The room was sealed so that the fire was extinguished by lack of oxygen. Throughout the test, no ventilation was provided and the source material was not removed to simulate a “worst case” scenario. The study was designed to ensure that any changes in the environment were the result of the Odorox hydroxyl generator.

Air samples to measure the specific types and quantities of VOCs present were collected immediately following the extinguishment of the fire. The first sample was collected without the hydroxyl generator being activated to act as a baseline for chemicals in the room. A series of samples were then collected after the hydroxyl generator was turned on. A slide arrangement was set up to allow the sample collection pump to be put into and taken out of the test chamber without having to unseal the room. The samples were analyzed by Prism Analytical Technologies, Inc. (PATI), an independent laboratory that specializes in industrial and environmental air quality.

The Oasis+ model of hydroxyl generators was used for this study and provided by the Odorox Hydroxyl Group. The hydroxyl generator ran during the study with the fan setting on high and the generator setting on low. The low setting was selected because of the size of the test room.

The sample results show a nearly constant reduction in total VOCs (TVOCs) from 48,000 nanograms per liter of air (ng/L) immediately after the fire, to 14,000 ng/L two hours after the hydroxyl generator was turned on, to 2,600 ng/L eight hours after the generator was turned on, to 1,600 ng/L five days after the burn.

Over the course of the test period the types of VOCs recovered varied considerably. Specifically, the data showed that over time the more complex chemical molecules were being changed through chemical reactions into simpler compounds. The study confirms the science provided by the manufacturer that hydroxyls and other radicals eliminate odors and reduce VOCs by breaking down their chemical structures. The levels of individual VOCs in this study, including the intermediate or new compounds formed during the breakdown of VOCs and odors, were well below the permissible exposure levels (PEL) published by OSHA. The study would suggest that the Odorox hydroxyl generator makes the work environment healthier for restoration contractors by reducing the TVOCs after a fire.

The test data matched with the visual and olfactory results with one major exception. The strength and pungency of the smoke odors evaluated by the testers decreased in the first two hours after the hydroxyl generator was turned on. However, over the next six hours, both the strength and pungency of the odors increased before slowly tapering down over the next three days. After five days, without source removal or ventilation, the odor was eliminated and the room smelled fresh. It was also noted that the visible residue that had been observed on the walls of the test chamber had dissipated almost completely.

2.0 Introduction

Wonder Makers Environmental was contacted by Odorox Hydroxyl Group to assist them in providing relevant information to the restoration industry regarding the air quality of post-fire environments. Odorox Hydroxyl Group was also interested in determining if there were any potential risks to restoration contractors when working in such situations. In response, Wonder Makers Environmental suggested a two-part approach. It was recommended that the initial phase of the project be a review of existing literature related to indoor air quality (IAQ) and the risks associated with working in structures that have suffered from fire and smoke damage.

The goal of the first part of the research was to answer important questions about the types and quantities of residual contaminants that may be present in structures at the time that restoration work is undertaken. Specifically, given that smoke odor is often present and addressed

throughout the restoration process, the research paper was suggested to answer relevant questions such as:

1. Does the available information suggest that certain harmful contaminants or intermediate compounds are typically present in a fire-damaged structure?
2. Is there any research that suggests that environments subjected to fire restoration are generally safe during the various stages of restoration work, or does it suggest that most are potentially unsafe?
 - a. Understanding that every fire is different, and because it always makes sense to err on the side of safety, are there certain types of fires or time periods after fires that are more dangerous?
3. Is there any consensus in the current body of knowledge regarding the use of personal protective equipment during the restoration of fire-damaged buildings—especially during the initial cleaning phases?
 - a. Is the risk to restoration workers and the utilization of personal protective equipment related to specific cleaning methods used during remediation?

As such, an extensive literature review was undertaken to determine the types and levels of contaminants that were present in a building following a fire loss (see the white paper completed in April 2015 entitled *Understanding the Hazards of Fire Residue Encountered During the Restoration Process*, attached as Appendix D). That review of currently available literature uncovered significant research regarding the types of contaminants that are produced during building fires, as well as the type and extent of airborne and surface contaminants that are produced in such conflagrations. A wide variety of noxious materials were identified from multiple studies, with the consistent warning that attempts to fully characterize hazards associated with fire losses are inherently limited compared to the vast array of products that can be impacted by fire and the individual progression that each structure fire takes.

Identifying the large variety of hazardous products produced during a structure fire (including aldehydes, esters, halogenated alcohols, hydrocarbons, nitro-nitriles, ketones, aromatics, sulfides, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, dioxins, etc.) led to the recommendation that personal protective equipment should be utilized by restoration professionals working on such projects.

Despite the thoroughness of the literature review, the study showed that there is little current research related to reducing the impact of airborne contaminants in such buildings by the use of hydroxyl generators. As such, testing in actual or simulated fire conditions was recommended as a follow-up to the initial research. An important aspect of the testing was to determine if the “cascade effect” discussed by the manufacturers of the generators as an aspect of the chemical oxidation process for the contaminant/odor reduction process actually diminishes the hazardous

compounds. It was also designed to determine whether the use of a hydroxyl generator puts restoration workers at any further risk.

Using the information obtained from the Part One study, Wonder Makers designed and conducted a second study to provide further information for the industry. The goal was to conduct a “practical science” study to evaluate the use of the Odorox hydroxyl technology and the possible impact it has in post-fire environments. In this case, the project involved the construction of a simulated finished interior space that was contaminated with fire/smoke byproducts. Numerous samples of VOCs were collected from the fire-damaged space over time in order to gauge the impact that a hydroxyl generator has on a real-world post-fire environment.

This report completes Part Two of the project.

3.0 Background Information on VOCs

Carbon-containing chemicals that release gas or vapors into the air under normal circumstances are often referred to as VOCs. Volatile organic compounds can be emitted from both solids and liquids at room temperature. Because many household items contain VOCs the Environmental Protection Agency (EPA) has noted that concentrations of such chemicals are consistently higher indoors than outdoors. In fact, one study by the EPA found indoor levels of VOCs up to ten times higher indoors—even in locations with significant outdoor air pollution sources such as petrochemical plants. It is also important to note that there are natural sources of VOCs, as well as those that are released from manmade products, such as gases that are released as a byproduct of fungal growth.

Currently, while there are U.S. standards for certain VOCs, there is no specific U.S. standard for the PEL for TVOCs. Even though research and opinions have been published for more than 30 years, questions regarding safe levels still remain and are currently being discussed. However, it is possible to recommend reasonable, workable limits until a specific standard is established.

Research generally seems to agree that less than 500 nanograms per liter of air (written as <500 ng/L) represents an “acceptable” TVOC level and that greater than 3,000 nanograms per liter of air (>3,000 ng/L) represents a “hazardous” TVOC level. Recognized symptoms above 3,000 ng/L generally include drowsiness, eye and respiratory irritation, general malaise, headache, nausea, and exacerbation of symptoms of respiratory ailments.

There is little consensus among experts regarding the hazards involved with levels between 500 and 3,000 ng/L. Part of this problem rests in the fact that many people enjoy VOCs from perfumes and odorants (cleaning products, scented candles, potpourri, air fresheners, etc.) that increase the background VOC level, while other people are not so inclined and may actually

suffer from nausea, headaches, and other symptoms as a result of exposure to such commonly used VOCs. In addition, some information indicates that typically acceptable levels in this middle range are substantially greater than the trigger level for symptoms in chemically sensitive individuals.

Many of the studies reviewed in Part One of this project confirmed that heating or burning various products can release, or even create, VOCs. While other compounds that do not fall into the broad category of VOCs (*e.g.*, PCBs) are created during fires in structures, the selection of VOCs as the test agents for this study was based on the fact that VOCs make up the largest single class of chemicals present in the atmosphere of fire-damaged structures. The wide variety of compounds included in the VOC classification also played a role in choosing the sampling strategy, as measuring various types of VOCs would help to determine possible chemical reactions from the oxidation that occurs when hydroxyl radicals come in contact with other airborne chemicals

4.0 Background Information on Hydroxyl Radicals

Hydroxyls (OH) are molecules consisting of one oxygen atom and one hydrogen atom. They are naturally occurring and are created in our atmosphere when the sun's ultraviolet (UV) rays react with water vapor. In the simplest of terms, different wavelengths of light interact with water (and other chemicals) in the air and produce simpler byproducts known as reactive oxygen species (ROS). One of the main types of ROS is hydroxyl radicals, which are typically formed when UV rays break down ozone and water droplets and then recombine. This new chemical mixture is very unstable and within seconds it will seek other contaminants in the air to react with (or on surfaces if the process occurs near the ground or indoors). These reactions typically break down larger molecules (whether chemicals like VOCs or minute structures such as virus and bacteria) so well that scientists have dubbed hydroxyl radicals the "detergent of the atmosphere".

Through the use of patented UV technology, Odorox replicates the natural production of hydroxyls. Ambient air is drawn through the irradiation chamber of the machine where finely tuned UV optics break apart humidity (H₂O) to form hydroxyls. The decomposition of volatile organic and inorganic compounds by these hydroxyl radicals involves a complex series of free radical oxidation steps that gradually result in the loss of individual carbon atoms to eventually form carbon dioxide (CO₂). Many scientists describe this process for simplicity as the cascade effect.

Hydroxyl radicals are very unstable oxidants because they are missing an electron in the outer shell and are driven to regain one electron to restore their very stable state. In general, hydroxyls recombine with other compounds within 22-44 milliseconds to form peroxy-free radicals. These new radicals are still unstable and rapidly react with VOCs and inorganic gases. However, these

peroxy radicals are more stable than the hydroxyl radicals and able to travel farther away from the reaction chamber to react with VOCs and microorganisms in the ambient air outside of the Odorox generator. Peroxy radicals can also rapidly form oxy radicals in ambient air. Oxy radicals are powerful oxidants and even more stable than their peroxy counterparts, and, therefore, are able to travel even farther from the generator to react with microorganisms and other VOCs. Other oxidants created downstream are even more stable. The creation of hydroxyls and these types of intermediate oxidants are the means by which the Odorox products are able to penetrate and treat structures and contents at a distance from the device. In short, the term cascade effect indicates that some of the airborne chemicals that come in contact with the oxidizer themselves become unstable and cause secondary reactions with still other compounds in the air.

While not directly related to hydroxyl radicals or fire residue, previous tests where ozone was used to address new carpet smell showed that the total concentration of organic chemicals in the air increased rather than decreased after the introduction of ozone. Numerous governmental and academic organizations state that additional research is needed to more completely understand the complex interactions of indoor chemicals in the presence of oxidizers, including ozone, hydroxyl radicals, and hydroperoxides. It is important to realize that hydroxyls break apart odors at the molecular level. As such, hydroxyls do not mask, cover up, filter, or trap odors—they create chemical reactions that eliminate them.

While hydroxyl generators are used in many different areas of the restoration industry, including fires, floods, mold contamination, and pet odors, there is one market segment where airborne contaminants are the most pernicious. Fire restoration has potential risks greater than many other aspects of the remediation industry because of the large number of compounds that are produced and sent airborne when materials are burned.

Since the use of hydroxyl generators for fire restoration constitutes a worst-case scenario, fire residue was used for this study of the impact of hydroxyl radicals as part of the restoration process.

5.0 Description of the Test Chamber Setup

A simulation room was constructed at the Wonder Makers Environmental facility in Kalamazoo, Michigan, and used in a smoke study conducted for the Odorox hydroxyl generator. A test chamber was necessary to determine the effect of hydroxyl radicals on smoke and fire residue. The chamber was constructed out of studs and drywall to represent a small room or house. The approximate dimensions were 9' x 9' x 7', with a standard door installed on the west side of the room. There were no windows, vents, electrical outlets, or other penetrations cut into the drywall other than a 4" x 6" opening to allow insertion of a sampling pump and collection media.

Although not finished to a professional standard from an appearance standpoint, the drywall, mudding, and taping were completed such that there were no obvious air infiltration/exfiltration points (although the burn conducted for the experiment did reveal a small gap about four inches long where some smoke escaped). After a primer coat was applied, different types of paint were applied to the walls. Oil based paint, latex, and cleanable paint were utilized in order to evaluate whether different finishes react similarly when exposed to smoke and hydroxyls.

Other than the entry door, the only opening into the test chamber was a small cut-out in the west wall to allow access for the sampling pump. A double curtain flap made of 6-mil plastic was used to provide a basic seal on the opening. The double flap worked well, as no obvious evidence of smoke leakage was observed during the testing except when the flaps were moved to place or remove the sampling pump.

A narrow wood platform was used to place a small air sampling pump inside the simulation room. A five-foot long “slide chute” was installed in the test chamber. This 2' x 4' board with side rails allowed the sampling pump to be positioned in the same location for each sample. It also positioned the sample just above waist height, which would be the lower limit of the breathing zone.

A hydroxyl generator was supplied by Odorox Hydroxyl Group for the test. They provided a new Oasis+ unit for the experiment. At the beginning of the test the generator had a run hour indicator of 00000.1. At the end of the experiment the indicator dial read 00170.0

The manufacturer's instructions were followed in order to prepare the hydroxyl generator for use. White foam protecting the machine's UV optics was removed from inside the machine. After the foam packing around the optics was removed, the two wiring harnesses were connected to the optics. Following the preparations described in the manufacturer's instruction the generator was tested. The indicator light confirmed that the optics chamber portion of the machine was operating, while the noise of the fan and air exiting the exhaust vent confirmed the functionality of the generator's fan.

The Oasis+ hydroxyl generator was prepared for the test by presetting the controls. The generator was turned to low and the fan speed to high. The low setting means that only one of the two UV optics was operating for this study. The decision to set the generator on low was based on the small size of the test chamber. The fan speed was selected because the test would involve intentionally dense smoke and no ventilation outside the chamber, as would normally occur in a restoration project.

The hydroxyl generator was set approximately ten inches off the floor and approximately 2½ feet away from the test location. Given the size of the test chamber and the central location of the samples this was the maximum separation distance.

In order to avoid having to enter the chamber after the burn was initiated and the room sealed, the hydroxyl generator was plugged into an extension cord with a GFCI. Operation of the generator was controlled by the GFCI switch outside the test chamber.

A simple charcoal barbeque grill was used to contain the fire used for the smoke test. A Uniflame portable grill was placed into the simulation room. A starter fire was built with newspapers and wood shims. In order to simulate an actual house or office fire, a variety of building products were assembled to add to the starter fire. These included Romex wire, plastic electrical boxes and switch plates, foam insulation, a plastic paper towel holder, pieces of painted drywall, and scraps of fabric.

Although strict precautions were taken in regards to the preparation and implementation of the test burn, additional safety features were employed during the critical phases of the test. During the actual burn portion of the experiment two individuals served as fire watchers, with ABC combination fire extinguishers at the ready. A 20-gallon foam generator was utilized as secondary protection during the burn. It was filled with water and a flame retardant material that foams when sprayed. Neither the fire extinguishers nor the foamer were used during the experiment.

A number of ventilation fans were set up near the test chamber in case smoke or odors escaped during the experiment. The fans were positioned so that any fugitive fire residues would be moved to the outside of the building. Despite the best efforts at sealing the test chamber, some emissions required the operation of the ventilation equipment.

Prior to the test burn, other pieces of equipment were assembled/prepared. The battery operated sampling pump specifically designed for VOC sampling tubes was bagged for protection with only the sampling port exposed. The pump was secured to a slide stick so that it could be quickly and easily moved in and out of the test chamber.

After the grill was positioned near the center of the test chamber (approximately eight inches from the air sample location), the materials for a starter fire were added. The starter fire was ignited and allowed to burn long enough to serve as an ignition source for the materials representative of items typically consumed in a small fire. The simulated household materials were then added to the starter fire inside the test chamber and allowed to catch fire.

After the composite fire was burning aggressively, the barbeque lid was closed. All of the air vents at the base of the grill and the top vent were left completely open. Within seconds dense black smoke began pouring out of the grill even as the test chamber door was closed and sealed.

Within twenty seconds of the door being sealed smoke was present in every part of the test chamber. One minute after the door was sealed the smoke and fire residue were significant enough to partially obscure the equipment in the test chamber. Smoke density and temperature indicated that the fire in the grill had been extinguished from lack of oxygen within nine minutes of sealing the test chamber door. At that point, the smoke density was so great that the sampling equipment was totally obscured within one foot of the entry point.

6.0 Sampling Protocol

A small low-volume air sampling pump (Prism Analytical Technologies Model PATI -100) with an attached glass sampling tube was connected to a long piece of wood. The pump was fitted with fresh batteries and turned on so that the pump was drawing 0.2 liters per minute. For each sample a VOC sorbent sampling tube from Prism Laboratories was fitted tightly into the rubber orifice on the pump and run for exactly two hours in order to collect 24 liters of air. After being set up according to the laboratory's specifications, the air sampling pump and attached glass sampling tube were fed into the smoke-filled simulation room on the narrow wood platform. The samples were analyzed for the presence of total volatile organic compounds, total mold volatile organic compounds, and other contaminants.

Eight air samples were collected in the simulation room. Immediately after the fire was extinguished the first two-hour VOC sample was positioned in the test chamber. It served as a background sample as the hydroxyl generator was not activated during the run time of this first sample. The decision to allow a short waiting period is consistent with restoration work since very few restoration projects start within minutes after the fire is extinguished.

Two hours after the test fire had burned out the hydroxyl generator was turned on and the second sample was started. Four hours after the test burn was completed a third sample was started. Five VOC air samples were collected at two-hour increments after the test burn. Three additional samples were collected, starting 24 hours after the burn, then 48 hours after the burn, and five days after the burn.

The samples were packaged according to the laboratory's directions and shipped to PATI for analysis. A more detailed analysis of the first two samples was requested in order to provide a description and quantification of all VOCs recovered from the samples. For the other six samples only the top ten VOCs recovered were quantified. This is important to note when reviewing the summary chart of sample results (Appendix C), as the total level of VOCs is greater than the sum of the listed compounds since chemicals outside of the top ten contribute to the totals.

7.0 Observations

A number of observations related to the sample process and outcome were made. Some of the most critical observations made in regards to the experiment include:

- 7.1 The odor from the fire in the test chamber as the representative burn items were placed on the starter fire before the chamber was sealed was described by one of the fire watch bystanders as “nasty plastic smoke”. Other descriptions offered by those assisting with the process included “styrene”, “acid”, and “sharp”.
- 7.2 After the composite fire was burning aggressively, the barbeque lid was closed. Within seconds, dense black smoke began pouring out of the grill even as the test chamber door was closed and sealed.
- 7.3 Within twenty seconds of the door being sealed smoke was present in every part of the test chamber.
- 7.4 One minute after the door was sealed the smoke and fire residue were significant enough to partially obscure the equipment in the test chamber.
- 7.5 Smoke density and temperature indicated that the fire in the grill had been extinguished from lack of oxygen within nine minutes of sealing the test chamber door.
 - 7.5.1 At that point the smoke density was so great that the sampling equipment was totally obscured within one foot of the entry point.
- 7.6 A small amount of smoke leakage was visible at a seam between the west wall and ceiling.
 - 7.6.1 The area leaking was approximately four inches long.
 - 7.6.2 Visible smoke leakage ceased shortly after the fire self-extinguished.
 - 7.6.3 No smoke leakage was observed over the majority of the experiment despite the fact that smoke was visible in the air of the test chamber for over 30 hours after the fire had gone out.
 - 7.6.4 The area of visible smoke escape is believed to be the spot where fire residue and odors continued to migrate from the test chamber despite the fact that visible evidence of such movement of contaminated air had ceased.
- 7.7 From an olfactory standpoint, the odor in the test room seemed to get worse a few minutes after the hydroxyl generator was turned on (two hours after the burn). The increase in intensity and pungency continued for several hours and then tapered off, only to increase again in the time interval between samples six and seven.
- 7.8 Visually it appeared that substantially more clearing of the smoke had occurred in the two hours that the hydroxyl generator unit had operated as compared to the two hours when the chamber was sealed and the equipment had not yet been turned on.

- 7.9 Smoke residue was still visible in the test chamber for 24 hours, even with the Oasis+ machine in operation for 22 hours of that time.
 - 7.9.1 No ventilation was instituted as part of the experiment even though such a step is a normal part of fire restoration. Eliminating the ventilation created a worst-case scenario for the project and ensured that it would not assist with a decrease of TVOCs or odors.
- 7.10 48 hours after the burn (46 hours after the hydroxyl generator was turned on) the air in the test chamber appeared to be fairly clear, but there was still a significant burn odor in the chamber.
 - 7.10.1 Grayish/black residue was visible on several walls of the test chamber.
- 7.11 Five days after the fire (118 hours of operation of the Oasis+ hydroxyl generator) dramatic results had been produced. The fire odor had been eliminated and replaced with a clean, fresh smell.
 - 7.11.1 Multiple individuals verified this observation, including several women who were involved in the evaluation based on their more acute olfactory capability.
- 7.12 After five days without source removal or ventilation, but with the use of the Oasis+ hydroxyl generator, not only was the air clear and smoke odor eliminated, but visible residue that had been observed on the walls of the test chamber had dissipated almost completely.
- 7.13 Upon completion of the sampling, the test chamber was unsealed and a detailed review of the area conducted. The amount of unburnt material that remained after the fire had self-extinguished was greater than anticipated.

8.0 Sample Results

Complete sample results for the experiment are included as Appendix B. A summary chart of sample results is included as Appendix C. Even a cursory review of the summary chart shows that:

- 8.1 A wide variety of noxious VOCs were formed with just a small fire.
- 8.2 Without ventilation, visible contaminant levels stayed relatively high for over 30 hours.
- 8.3 With one exception (48½ hours after the burn), the data displayed a consistent decline curve in regards to TVOCs.
 - 8.3.1 Total VOCs dropped from 48,000 ng/L immediately after the fire to 1,600 ng/L five days later without any ventilation or removal of source material.
- 8.4 There was a close correlation between the main components recovered from the first two samples, but that correlation weakened the longer the hydroxyl generator ran.

- 8.4.1 In the first two hours of generator run time the top eight VOCs recovered had the same rank order, although at significantly lower levels after the generator was operating.
- 8.5 The hydroxyls appeared to create intermediary products as they reacted with the air contaminants to reduce the overall total VOCs.
 - 8.5.1 Naphthalene showed a steady decrease from 560 to 9 ng/L over the course of six samples.
 - 8.5.2 Neither hexanal nor 2-Ethyl-1-hexanol were present in the sample collected before the hydroxyl generator was started. After the addition of the hydroxyls, the compounds were not only present, but increased over a series of samples before the concentrations dropped off.
 - 8.5.3 The appearance of different compounds and increasing quantities of some of those compounds as the Odorox Oasis+ unit operated in the test chamber appears to confirm the manufacturer's claim that intermediary chemicals are produced by the oxidation action of the hydroxyl radicals that leads to a "cascade effect".
- 8.6 The rise in the total level of VOCs between samples collected at 22 hours and 48 hours after the burn was substantial.
 - 8.6.1 VOC levels doubled, rising from 1,300 to 2,600 ng/L.
 - 8.6.2 Only five of the top ten recovered compounds were consistent between the two samples.
 - 8.6.3 The most dramatic difference was in the level of acetone recovered from the two samples. At 22 hours after the burn 75 ng/L were recovered, while 610 ng/L were present at the 48 hour mark.
- 8.7 In absolute terms, all the results are relatively low—significantly below general occupational thresholds.
 - 8.7.1 The sample data is presented in nanograms per liter of air; which is the general equivalent to parts per trillion (ppt) of air. In general, occupational exposure limits for specific VOCs are listed in parts per million (ppm). The conversion factor to move from ppb to ppm is to divide the ppb result by 1,000.
 - 8.7.2.1 It is difficult to do a direct comparison of the total levels of VOCs listed in the various lab reports in ng/L to ppb because the molecular weight of the compound is necessary for converting the results for a gas (as compared to liquids and solids, which have a straightforward mathematical conversion). However, since the total is a combination of many different compounds with varying molecular weights, many scientists use a compound with a molecular weight near the middle of the

range of the most prevalent VOCs as an average to determine the overall level of VOCs in parts per billion nomenclature. The most frequently used chemical for such a conversion is hexane with a molecular weight of 86.2.

8.7.2.2 Using hexane as a conversion factor, the total level of VOCs captured during the experiment's eight samples can be expressed as follows:

Sample number	Total VOCs		
	Nanograms per liter of air (ng/L)	Parts per billion (ppb) based on molecular weight of hexane	Parts per million (ppm) based on molecular weight of hexane
01	48,000	13,418	13.4
02	14,000	3,913	3.9
03	4,300	1,202	1.2
04	3,000	839	0.8
05	2,600	727	0.7
06	1,300	363	0.4
07	2,600	727	0.7
08	1,600	447	0.4

8.7.2.3 The comparison can be continued by looking at the regulated and recommended levels of hexane and comparing that to the overall levels of VOCs recovered in the samples.

8.7.2.4 OSHA's current PEL for hexane is 500 ppm, while the NIOSH recommended exposure limit (REL) is 50 ppm.

8.7.2.5 The estimates in the table show that the total VOC level at the worst conditions are 37 times lower than the OSHA PEL and almost four times lower than the NIOSH REL. At the end of the experiment the total VOCs are estimated by this method to be 1,250 times lower than the OSHA PEL.

8.7.2 Another example, sample 1, has m,p-Xylene at 1,000 ng/L, and by sample 3 that compound is down to 52 ng/L.

8.7.2.1 Because of the molecule weight of this compound these values equal approximately 230 and 12 parts per billion. By comparison, the NIOSH REL for m,p,-Xylene is 100,000 parts per billion (100 parts per million).

8.7.3 The concentration of benzene in the first sample was 2,200 ng/L, and it dissipated to undetectable levels after ten hours.

8.7.2.1 This is the largest observed value for a single compound that has a corresponding OSHA PEL.

8.7.2.2 The OSHA limit for benzene is 10 parts per million of air over an eight hour time frame.

8.7.2.3 The conversion from nanograms per liter takes into account the molecular weight of the compound, and the laboratory indicated that 2,200 ng/L was 690 parts per billion or 0.69 parts per million.

8.7.2.4 This means that, at worst, with dense smoke in the room, the regulated compound recovered at the highest level was 15 times lower than the current OSHA regulatory limit.

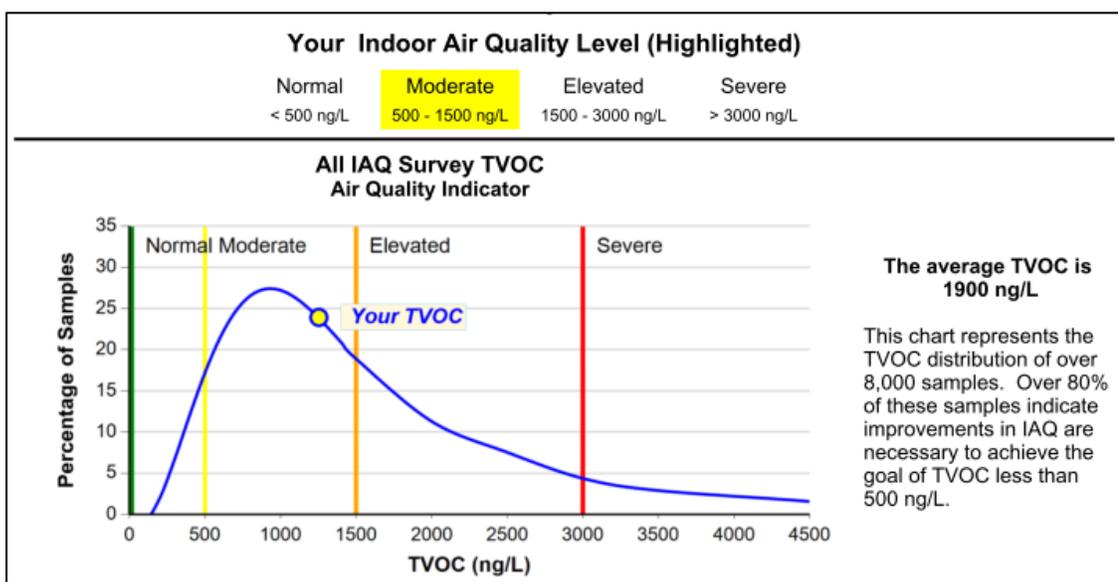
8.8 Even though the results are low compared to occupational exposure levels, VOCs, particularly ones that register with the olfactory nerves, can be sensed at the low levels recovered from many of the samples.

8.8.1 There was clear anecdotal evidence of that assessment during the project. Multiple observers characterized the odors at the time the sample results were between 2,600 ng/L and 3,000 ng/L as “pretty intense”, and “certainly not livable”.

8.8.2 In addition to the discomfort factor, there is a growing body of evidence that VOC exposures are much more dangerous at low levels than what the current U.S. Occupational Standards allow.

8.8.2.1 This broader approach to evaluating the data, which takes into consideration multiple recommendations from respected global organizations, is why the laboratory is flagging some of the results as “severe” and “elevated”.

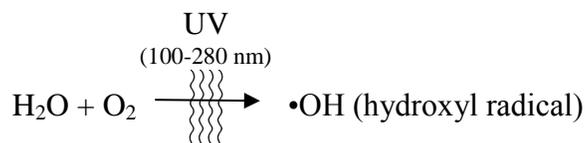
8.8.2.2 The lowest levels of total VOCs recovered during the experiment are described as “moderate” by PATI because they are above “normal” for living environments. (See sample chart from the lab data below.)



9.0 Examples of Likely Chemical Reactions

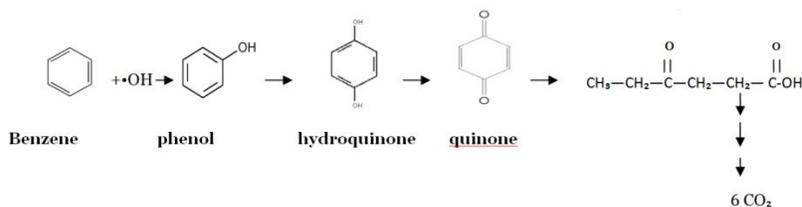
Many chemical reactions that involve oxidizers are “reductions”, where complex chemical compounds are broken down (*i.e.*, reduced) into two or more less complex compounds. Of the primary chemicals recovered during the experiment with the Odorox hydroxyl generator, naphthalene with two complete carbon rings linked together would be one of the more complex materials. Conversely, acetone and acetic acid would be two of the simpler intermediate VOCs. From there, the oxidation would continue to break down the chemicals to final products such as carbon monoxide (CO), carbon dioxide (CO₂), and water (H₂O).

As detailed earlier, and shown by the illustration below and in simple terms, the Odorox technology produces hydroxyl radicals when oxygen and water vapor in the air react with high energy and short wavelength ultraviolet light (UVC). The unstable, short lived, oxygen/hydrogen molecule that results is called the hydroxyl radical.



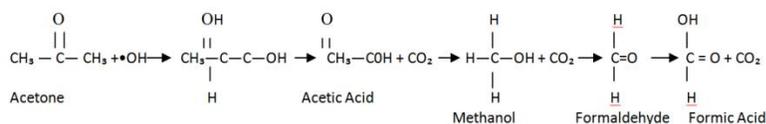
Because it is unstable, the hydroxyl radical seeks to combine with other compounds in the air and on surfaces. The hydroxyl radical is so aggressive in recombining with other materials that it will even break up rather stable compounds, such as naphthalene, which has a double ring of carbon atoms as its base chemical structure. The sample results showed that naphthalene was attacked rather quickly and had been reduced by over 80% within the first two hours of operation of the Odorox hydroxyl generator (from 560 ng/L to 100 ng/L). Naphthalene was completely eliminated within 48 hours of operation of the hydroxyl generator.

Several examples of the most likely reaction processes that were going on inside the test chamber can be illustrated. Benzene is another relatively stable compound with a single carbon ring as its primary chemical configuration. When impacted by a hydroxyl radical, the addition of oxygen and hydrogen atoms creates a new chemical: phenol. When the phenol reacts with an additional hydroxyl radical, another new compound, hydroquinone, is formed. However, this molecule is relatively unstable and actually breaks open the carbon chain so that one of those atoms can bond with the hydrogen to form dihydrocarbon (*i.e.*, CH₂, also known as methylene), leaving behind a simpler chemical called quinone. Once the carbon ring of the original benzene is broken open, it is more easily reduced by other hydroxyl radicals. As the oxygen and hydrogen atoms recombine with the various combinations of carbon, a number of intermediates are formed until the end result is six molecules of carbon dioxide (CO₂).



Acetone (chemical formula C₃H₆O) is both a product produced by the burning process and an intermediary compound created when hydroxyl radicals break down other molecules. This dual source is the best explanation for why the sample results for acetone showed a steady downward trend over the course of the first six samples, but then spiked up as the total level of VOCs also increased. Such reactions of carbon compounds also would explain the reappearance of such chemicals as toluene (C₇H₈) later in the sampling, after that specific chemical had been eliminated during the early addition of hydroxyl radicals.

Once the hydroxyls had reduced larger molecules down to the acetone stage, the breakdown into inert materials would proceed rather quickly. The diagram below shows a likely process where acetone is reduced in sequence to acetic acid, methanol, formaldehyde, formic acid, and to a final stage of carbon dioxide.



10.0 Conclusions and Recommendations

According to the National Fire Protection Association, it is estimated that some 370,000 home fires occur each year, costing close to \$7 billion in total property damage. Many of these fires, however, start and are contained in a certain area of a home or business. Even though containment eliminates the necessity for complete demolition and reconstruction, it is still necessary for proper cleaning of soot and smoke to commence, in order to restore the property to a pre-loss condition.

A large number of high quality research studies have been conducted and confirm that structure fires create a wide variety of hazardous airborne compounds, and that firefighters are at significant risk of unsafe exposures both during and immediately after the fire. However, far less data is available to develop a risk assessment related to exposures for restoration contractors who enter a burnt structure. Nor is there much scientific information that explores the impact that various fire restoration practices (*i.e.*, wiping with smoke sponges, washing with chemical

solutions, fogging with deodorizers, using oxidizers such as ozone machines or hydroxyl generators, etc.) have on the quality of the indoor air for either the contractors or the occupants.

This experiment addresses some of those deficiencies by providing detailed data that describes the types and levels of VOCs produced by a small fire in an enclosed space. It also examines the impact that operating an Odorox hydroxyl generator in that type of environment has on the chemical compounds. Extrapolating the results from this initial study to suggest recommendations for appropriate restoration work practices is possible because the experiment was set up as a worst-case type of environment where burned building materials were not removed and no artificial ventilation was utilized to assist with the odor reduction.

Given that OSHA does not provide a regulatory limit for TVOCs, but provides guidance according to specific airborne chemicals, it is difficult to say that the sample results conclusively prove that restoration contractors are not at risk of violating workplace standards when conducting fire restoration activities, whether or not a hydroxyl generator is used. Nevertheless, many signs from this experiment indicate that workplace safety and health regulations are not being exceeded. As shown by the examples in section 8.7 of this report the highest concentrations of regulated VOCs were recovered after the fire in a closed environment that was still filled with dense smoke. Since no restoration worker would be able to work in such conditions without respiratory protection, and since the VOC levels dropped rapidly after the Oasis+ unit was turned on, the sampling data strongly suggests workers conducting fire restoration efforts are not exposed to chemical concentrations in violation of OSHA permissible exposure limits. Even so, the levels of VOCs documented by the sampling are significant enough to raise concerns for the health of the workers when compared to other occupational and non-occupational guidelines.

For example, the laboratory utilized for analysis of the samples specializes in assisting individuals with indoor air quality problems related to VOCs. Their practice is to label any sample result of TVOCs above 3,000 ng/L as “severe”. By comparison, in this experiment the VOC level started at 48,000 ng/L following the start of the fire and fell to 14,000 ng/L four hours after the burning material had died out. The TVOC level did not fall below the 3,000 ng/L threshold until the hydroxyl generator had run for over six hours.

This indicates that the current industry recommendation to provide basic personal protective equipment for fire restoration workers, including respiratory protection, should be continued. (See, for example, various Restoration Industry Association, Red Cross, National Fire Protection Association, and other documents which recommend that gloves, a protective mask, long-sleeved shirts, and long pants be worn on site to minimize contact with ash and other fire residue during clean-up.) These common sense safety procedures make even more sense when the data shows that the individual VOC exposure levels are significantly below occupational exposure levels,

but the combined or TVOCs were significantly above generally recommended health levels for normal occupants, especially before the hydroxyl generator was turned on. Even though restoration workers are not in a house 24/7 like some occupants, which increases overall exposure to airborne chemicals, they often work extended hours and may regularly work in these types of environments.

Further, it is important to note that the support for reinforcing the industry recommendations to use basic PPE is based on the ambient conditions after a fire, not because a hydroxyl generator is used to address the IAQ concerns. The fact that the study indicates that the Oasis+ unit was helpful in breaking down the airborne VOCs (and surface residues) means that using such technologies during restoration work is likely to reduce the amount of time that it is necessary to use such PPE on the jobsite.

Another clear conclusion from the study is that there is a close correlation between the olfactory and the laboratory assessment of airborne contaminants after a small structure fire. Observer descriptions of the odor conditions indicated that the smells from the test chamber decreased after the initial wait time and activation of the Oasis+ unit, which is what the sample results showed. However, the olfactory evaluation appeared to detect the change in types of compounds as the hydroxyl reaction process progressed, as well as the increase in the level of TVOCs during the middle part of the experiment (1,600 ng/L after day two and 2,600 ng/L after day three). It should be noted that this increase may be attributed to the continued presence of source materials and the eventual attack upon these materials by the oxidants. Since the olfactory assessment is conducted in real time, it is a faster process than chemical sampling to determine the general timeframe for when it is safe to phase out protective equipment. This provides strong support to the restoration industry approach of using an absence of smoke odors as their primary evaluation tool to gauge the effectiveness of the fire repair effort. Therefore, the recommendation from these results is that fire restoration workers use personal protective equipment in the work areas until the smoke odor is eliminated. This olfactory criterion would be an indication that the TVOC levels are in the “moderate” or “low” range as described by PATI.

Clearly, the primary theories about using the Odorox hydroxyl generator to assist with fire restoration were proven by this experiment. The manufacturer has provided scientific research that indicates that substantial quantities of hydroxyls are produced inside the chamber of the machine and have indicated that the unit would reduce smoke odors by reacting with airborne chemicals and breaking them down. They also make the claim that the hydroxyl generator will be able to eliminate the odors absorbed by the surfaces and contents in a room. They have made this claim despite the fact that hydroxyl radicals are so short lived that they do not actually circulate around the treatment area. Instead, they state that the hydroxyl radicals create other oxidizers, which produce a cascade effect that completes the oxidation process. Based on a

review of previous scientific research the manufacturer noted that the primary byproducts of the hydroxyl radicals are organic peroxy and oxy radicals.

Although specific sampling for hydroxyl radicals and organic peroxy and oxy radicals was not part of the test design, the results of the VOC testing indicated that some sort of cascade process was occurring. The sample results demonstrated that the hydroxyl radicals have a positive effect on the safety of the environment by reducing the VOC levels after a fire. However, the breakdown does create additional types of byproducts, which is confirmation of the expected science and cascade effect. In this study, the quantities of all byproducts were significantly below OSHA standards and were in the very low parts per billion range.

When paired with the visual and olfactory results, the sample data indicates that source removal is critical for successful deodorization in a short period of time. The visual indication of soot breaking down off the walls at the same time that the odors and airborne levels of VOCs were increasing suggests that after the hydroxyl radicals break down all of the airborne contaminants, they begin working on the surface materials. This theory is further supported by the fact that the soot is incomplete oxidation of the source materials that were burned. Restoration contractors that utilize a hydroxyl generator to assist them with deodorization may encounter an increase in pungent odors as the equipment operates if all charred materials, soot, and other odor sources have not been removed. It is interesting to note the correlation of the increase in pungent smells to the increase in TVOCs measured. Such olfactory variations could actually act as a quality control measure to verify whether all of the fire-damaged building materials have been properly removed.

More important are the practical aspects of the process. The use of the Oasis+ hydroxyl generator sped up the process of VOC removal. It was obvious that the room was free of unpleasant odors and had a fresh scent by the end of the experiment, despite the fact that source material remained and no outside air ventilation was included. It was surprising to note the visible reduction in surface contamination without any physical removal efforts.

Despite setting up the experiment under a worst case scenario, it is recommended that the use of a hydroxyl generator, such as the Odorox Oasis+, be employed in conjunction with ventilation and source removal. Following standard restoration protocols to first ventilate the space well and quickly work to remove any burnt materials, in addition to utilizing a hydroxyl generator to lower the VOC levels to ambient outdoor levels, would be better than requiring the machine to do all the work of odor reduction.

11.0 Appendices

Appendix A. Sample Collection Log

Appendix B. Sample results from Prism Analytical Technologies, Inc.

Appendix C. Summary chart of sample results

Appendix D. *Understanding Hazards of Fire Residue Encountered During Restoration Process*

Appendix E. Photograph Log

12.0 Certifications

David A. Batts currently serves as Director of Environmental Services for Wonder Makers Environmental. His background includes education in the liberal arts and a variety of life experiences. Dave is a certified Mold Remediation Supervisor and also holds other certifications related to indoor air quality investigations and abatement. He has been involved in remediation of hazardous indoor environments as a contractor, inspector, project manager, asbestos instructor, and laboratory analyst since 1971.

Michael Pinto provided oversight and generated the report for this study. Mr. Pinto's post-graduate training is in Public Administration and Environmental Engineering, and, in addition to his scholastic achievements, he holds the titles of Certified Safety Professional and Certified Mold Professional. He is a member of the American Society of Safety Engineers, Restoration Industry Association, American Industrial Hygiene Association, Indoor Air Quality Association, and the Cleaning Industry Research Institute. Mr. Pinto is the author of over 215 published technical articles and has successfully conducted industrial hygiene/indoor air quality investigations since 1988.

Prism Analytical Technologies, Inc. (PATI), the creator of the IAQ Home Survey used in this study, conducted the sample analysis. For over 20 years Prism's advanced lab, FTIR expertise, and proprietary testing technology have benefited Fortune 500 companies and IAQ professionals across the country and internationally. PATI is accredited by AIHA LAP, LLC.

Michael A. Pinto, CSP, CMP
CEO

David Batts
Director of Environmental Services