**Joe Spurgeon, Ph.D., CIH**
**Bayshore Environmental**
**www.expertonmold.com**
**jospur46@gmail.com**

# WILDFIRE SMOKE:
## POST RESTORATION ASSESSMENT OF RESIDENTIAL HOUSES

Property Locations: Six Houses in Bastrop, Texas Exposed to Wildfire Smoke
Two houses in Malibu, California Not Exposed to Wild Fire Smoke

Report Date: November 30, 2012

Joe Spurgeon
Joe C. Spurgeon, Ph.D., CIH

## SUMMARY

The objective of the study was to determine if wildfire smoke contaminants could be detected in post-restoration houses eight-months after the wildfire. Eight houses were included in the study, including two unexposed control houses and six smoke-exposed houses. The six exposed houses included two houses professionally restored, three houses cleaned by the owner, and one house that had not been restored and was unoccupied.

Tape-lift samples were collected from hard surfaces to measure the percent of soot and char by polarized light microscopy. The percentage of soot varied from less than 1% in professionally restored houses to greater than 40% in the owner-restored and unrestored houses. The percentage of char varied in a comparatively narrow range between 5% and 15%.

Surface contamination was primarily assessed by sampling Elemental Carbon (EC), Organic Carbon (OC), and Total Carbon (TC) concentrations on surfaces using the NIOSH 5040 Method. Wipe samples were collected on hard surfaces by visually estimating the area, while micro-vacuum cassette samples were collected on soft-surface items using an area template. The concentrations of EC and OC on hard surfaces were associated with the reported level of restoration. Carbon concentrations collected from soft surfaces by micro-vacuum cassette were also associated with the level of restoration.

The presence of airborne contaminants was assessed by measuring the concentrations of 15 aldehydes using the NIOSH 2016 Method. The concentrations of acrolein, benzaldehyde, and formaldehyde were elevated in the post-restoration houses compared to concentrations in the unexposed control houses and the CDC/ATSDR Minimum Risk Level (MRL) for acrolein and formaldehyde. The concentrations of the three aldehydes were interpreted as indicators of hidden contaminants; and acrolein and formaldehyde were used to assess occupant exposure potentials. Occupant exposures to acrolein and formaldehyde were elevated relative to residential exposure guidelines even eight months after the wildfire; and the concentrations were consistent with the reported symptoms of respiratory distress and eye irritation.

## 1.0 INTRODUCTION

**Site Visit.** A site visit occurred in July, 2012 to collect preliminary data on wildfire smoke contaminants in six houses in Texas. The site visit was limited to the collection of samples, and did not include an inspection of the properties. Site visits to two control houses in California were also conducted in August, 2012. The subject houses in Texas were described as having been substantially impacted by wildfire smoke and combustion products during a wildfire incident that occurred about September 3 & 4, 2011. The site visit occurred about eight months after the subject “Bastrop, TX” wildfire.

**Purpose.** The purpose of the site visit was to assess the interior space of the six smoke-exposed houses for the presence of residual combustion products typically associated with wildfire

smoke. This report describes the utility of two National Institutes of Occupational Safety and Health (NIOSH) sampling and analysis methods for assessing condition following the professional cleaning and restoration of houses exposed to wildfire smoke.

The study was conducted to determine if residual wildfire contaminants were (1) still detectable in the houses eight-months post-incident, and (2) at concentrations consistent with the reported symptoms. The objectives of the study included:

- Identifying contaminants that were potential indicators of post-restoration contamination;
- Using sampling/analytical methods with known characteristics that had been validated;
- The source of contaminants (cooking or wildfire);
- Associating the contaminant concentrations with the level of restoration of a house;
- Identify post-restoration acceptance criteria for assessing the structure and occupant exposure.

## 2.0 ASSESSMENT STRATEGY

A stratified sampling strategy was used in which the test houses were stratified (separated) by their reported level of restoration. The houses were ranked in Table 1 by the expected extent of residual wildfire contamination, decreasing from low (professionally restored) to high (not restored). These classifications were assigned based on the information received about the incident history, which was prior to an assessment of the sample data. Therefore, the actual status of a particular house may differ based on an assessment of the sample results.

**Table 1: Group I Houses: Professionally Cleaned.**

| HOUSE | INTERIOR | CONTENTS | OCCUPANCY |
|---|---|---|---|
| 1 | Walls painted | Professionally cleaned | Occupied |
| 2 | Remodeled | Professionally cleaned | Occupied |

**Table 1: Group II Houses: Cleaned by the Occupant.**

| HOUSE | INTERIOR | CONTENTS | OCCUPANCY |
|---|---|---|---|
| 3 | Cleaned by occupant | Steam cleaned by occupant | Occupied |
| 4 | Remodeled (occupant) | Cleaned by occupant | Occupied |
| 5 | Cleaned by occupant | Cleaned by occupant | Occupied |

**Table 1: Group III Houses: Contaminated.**

| HOUSE | INTERIOR | CONTENTS | OCCUPANCY |
|---|---|---|---|
| 6 | Not cleaned | Not cleaned | Not occupied |

**Table 1: Group IV Houses: Controls [Not Smoke-Exposed].**

| HOUSE | INTERIOR | CONTENTS | OCCUPANCY |
|---|---|---|---|
| 7 | Typical cleaning | Typical cleaning | Occupied |
| 8 | Typical cleaning | Typical cleaning | Occupied |

# 3.0 METHODS AND PROCEDURES

## 3.1 Methods

The contaminants and sampling methods included in the study were listed in Table 2. The NIOSH sampling methods were selected because they were quantitative, standardized, validated, and could be applied in a consistent manner.

**Table 2. Contaminants and sampling methods**

| Contaminant | Method | Assessment |
|---|---|---|
| Char and Soot | IESO 6001 | Accessible Surfaces |
| Total Carbon | NIOSH 5040 | Accessible Surfaces |
| Airborne Aldehydes | NIOSH 2016 | Hidden Spaces, Occupant Exposure |

IESO: Indoor Environmental Standards Organization
NIOSH: National Institute for Occupational Safety and Health

**IESO Method 6001**. Tape-lift samples were collected from hard surfaces in each of the six smoke-exposed houses by an independent consultant prior to the subject site visit. The surface was micro-vacuumed using a foam-filled 37 mm cassette and a tape sample was collected from the foam. The tape sample was analyzed by Polarized Light Microscopy, and soot and char concentrations were reported as a percentage by visual examination.

**NIOSH Method 5040**. Combustion particulate was collected on a 37-mm glass fiber filter that had been heat treated to 700 ºC to remove organic binders. Since binders had been removed, the filter was easily degraded by rough surfaces. A circular area of 1.5 $cm^2$ was punched out of the center of the 10.8 $cm^2$ filter by the laboratory for analysis. ASTM Standard D6002 method specifies the use of TEM or SEM methods for the identification of carbon black. The NIOSH 5040 method specifies the use of Evolved Gas Analysis (EGA) to identify Elemental Carbon (EC), Organic Carbon (OC), and Total Carbon (TC = EC + OC). Sample media and analyzes were provided by ALS Environmental, Salt Lake City, UT.

**NIOSH Method 2016**. Airborne aldehydes were collected on SKC 26-119 adsorption tubes at an airflow rate of about 0.18 lpm for a period of 60 minutes, resulting in a sample volume of about 11 liters. The airflow rate was measured with a high-precision 0-500 cc/min rotameter that had been calibrated with a Bios DryCal flow meter. A high-volume air pump equipped with a bypass valve and SKC low-flow controller was used to achieve the low airflow rate (Figure 1). The sample was analyzed for 15 aldehydes, and results were reported in units of parts per million of air (ppm) and micrograms per cubic meter ($ug/m^3$).

**Figure 1. Hi-vol Pump Equipped with a Bypass Valve and Adsorption Tube Sampler.**

## 3.2 Procedures

**Hard Surfaces**. The heat-treated filters that were used as wipes were supplied in individual plastic cases. The filter was removed from its protective case using disposable latex gloves, the dry filter was folded into quarters, and the center of the filter was repeatedly wiped across an area estimated to be 4 square inches. An area template was not used since some surfaces were irregular. The dry filter was returned to the protective case and labeled. Samples collected from hard surfaces using wipe samples were reported in units of micrograms per sample (ug/sample).

**Soft Surfaces**. Soft-surfaces were sampled using a heat-treated glass fiber filter contained in a 2-piece 37 mm cassette at an airflow rate of 10 lpm. A 10 cm x 10 cm template was used to sample three separate areas on a surface, for a total area of 300 $cm^2$. Samples collected from soft surfaces were reported in units of micrograms per 100 square centimeters (ug/100 $cm^2$).

The filters contained in individual plastic cases used to sample hard surfaces, and the 2-piece cassettes used to sample soft-surface materials were illustrated in Figure 2.

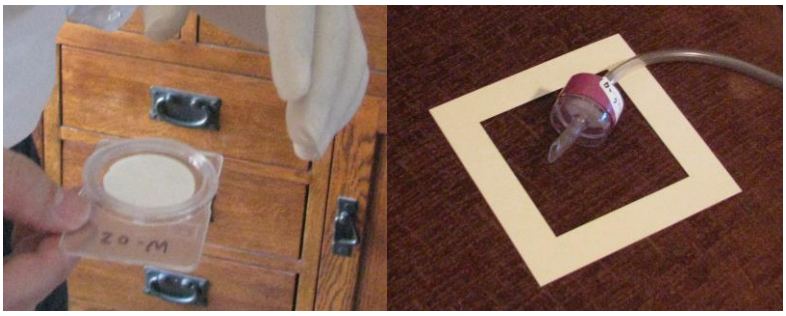


**Figure 2. Surface samples; hard surfaces and soft surface sampling methods.**

# 4.0 RESULTS AND CONCLUSIONS

## 4.1 Smoke Odors

Smoke-like odors were only detected in the unoccupied house # 6 that had not been restored. This house had been vacated soon after the subject incident, had remained unoccupied, and neither the interior nor the contents had been cleaned or restored during the eight months.

## 4.2 Occupant Health Effects

The occupants in the five occupied houses exposed to wildfire smoke were still reporting the symptoms in Table 3 eight months after the wildfire, although two of the houses had been professionally restored. It should be noted that the symptoms persisted even eight months after the subject wildfire.

**Table 3. Prevalence of Occupant Health Symptoms**

| Symptoms | Occurrence (%) |
|---|---|
| Stuffy, Runny Nose | 24 |
| Dry Cough | 21 |
| Asthma, Wheezing | 21 |
| Irritated Throat | 17 |
| Respiratory Distress | 10 |

## 4.3 Tape-Lift Samples from Hard Surfaces

IESO Standard 6001-2012 specifies the percent of char (%-char) as a primary indicator of surface combustion particulate in HVAC systems. Figure 3 describes the association between %-char on hard surfaces and level of restoration. The %-char was 4.5% in one restored house, about 11% in three restored houses, and 13% to 15% in the owner-cleaned and unrestored houses. The %-char on hard surfaces exhibited little variation with condition; and the narrow range made it a poor post-restoration indicator of the level of restoration.

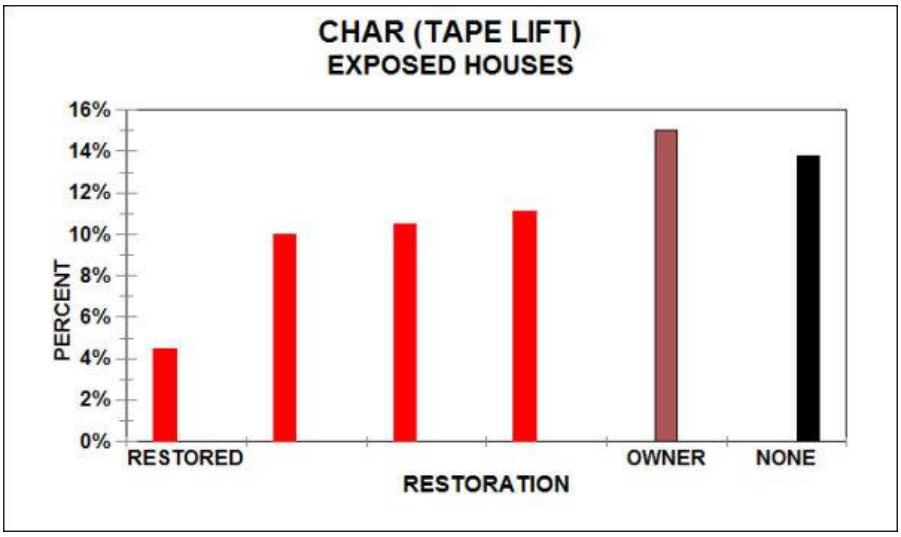



**Figure 3. Percent char on hard surfaces by tape lift.**

IESO Standard 6001-2012 also specifies the percent of soot (%-soot) as a secondary indicator of surface combustion particulate in HVAC systems. Figure 4 describes the association between %-soot on hard surfaces and the level of restoration. The %-soot was less than 1% in three restored houses, 8% in one restored house, and over 40% in the owner-cleaned and unrestored houses.

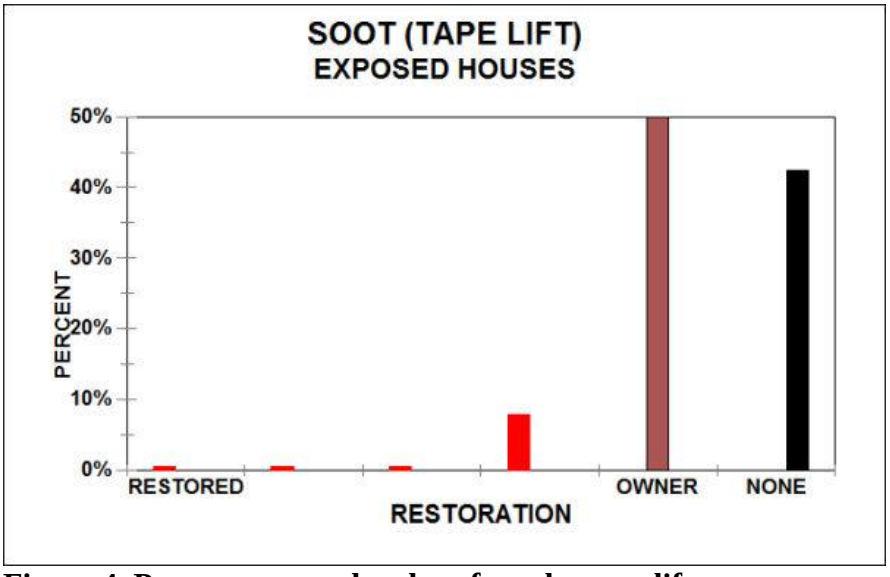



**Figure 4. Percent soot on hard surfaces by tape lift**

It was concluded that %-soot was associated with the level of restoration in these six houses. The %-soot was substantially less in the professionally restored houses (typically less than 1%) compared to the owner-cleaned house (50%). Therefore, professional cleaning appeared to be

more effective in removing soot from hard surfaces compared to owner cleaning. In addition, background soot was less than 1% by visual estimation.

The averaged %-soot and %-char data for the six houses are presented as a log-plot in Figure 5. The log-plot for char suggests that the concentration of 4.5% was drawn from a different distribution than the other five samples. The char concentrations of 10% and greater appeared to be drawn from a single distribution.

The situation for soot samples was less clear because of the small number of samples. Three houses had average %-soot concentrations below the limit of detection (LOD), defined as 1%. The remaining three houses were characterized as having moderate to elevated %-soot on hard surfaces. However, one conclusion was that background %-soot should be assumed to be less than 1% when professional restoration was performed adequately.

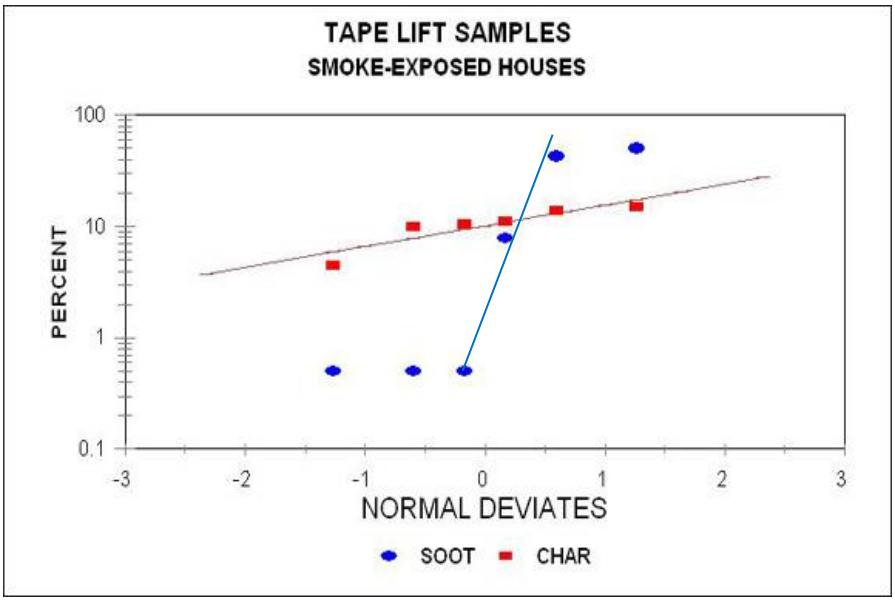



**Figure 5. Averaged Tape-Lift Samples Collected from Hard Surfaces.**

The individual results for soot and char collected from the six smoke-exposed houses were illustrated as a log-plot in Figure 6. The individual concentrations for each sample were graphed in rank order, and were not associated with a particular house.

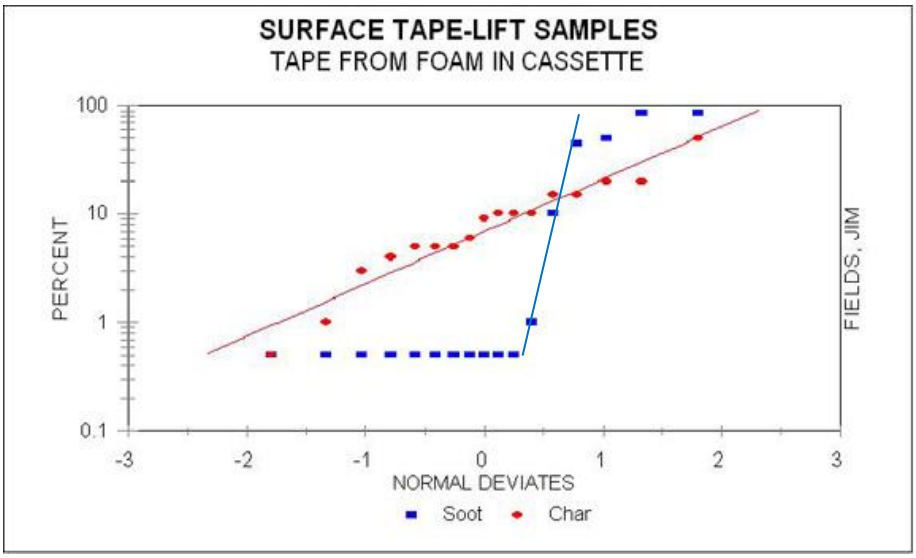



**Figure 6. Individual Tape-Lift Samples Collected from Hard Surfaces.**

Samples can be drawn from two concentration distributions, Uncontaminated or Contaminated. The linearity of the log-plot for those char samples with char concentrations greater than 3% suggested all those samples, except the two with the lowest concentration, were collected from the same concentration distribution; which was "Contaminated". The data suggested that char concentrations exceeding 3% for individual samples may have been an indicator of residual contamination.

The soot samples were in three groups, suggesting the samples were collected from both Uncontaminated and Contaminated distributions. A number of the soot concentrations were below the LOD, indicating background concentrations. However, a clear cut-point between uncontaminated and contaminated concentrations was not obvious for individual soot samples because of the small number of samples.

The averaged %-soot in each house were summarized in Table 4. A soot concentration of 5% or more was considered to be indicative of residual contamination. Based on this criterion, evidence of residual contamination was detected in Houses 1, 5 and 6.

**Table 4. Concentration of Soot in Surface Tape-Lift Samples (Percent).**

| HOUSE | GROUP | SOOT (%) | CLASSIFICATION |
|---|---|---|---|
| 3 | I | 0 | Not Elevated |
| 4 | II | 0 | Not Elevated |
| 2 | II | 0.5 | Not Elevated |
| 1 | I | 7.9 | Moderately Elevated |
| 6 | III | 42.5 | Elevated |
| 5 | II | 50 | Elevated |

The averaged %-char data for the six houses were summarized in Table 5. A char concentration of 3% or more was considered to be indicative of residual contamination. Based on this criterion, evidence of residual contamination was detected in all six Houses. Char provided little differentiation between remodeled house # 2 and unoccupied house # 6, while soot indicated a significant difference.

**Table 5. Concentration of Char in Surface Tape-Lift Samples (Percent).**

| HOUSE | GROUP | CHAR (%) | CLASSIFICATION |
|---|---|---|---|
| 3 | II | 4.5 | Moderately Elevated |
| 2 | I | 10.0 | Elevated |
| 4 | II | 10.5 | Elevated |
| 1 | I | 11.1 | Elevated |
| 6 | III | 13.8 | Elevated |
| 5 | II | 15.0 | Elevated |

## 4.4 Source of Surface Particulate

Assessing the probable source of the surface particulate was based on the concentrations of TC, OC and EC. The OC/TC ratio, the percent of EC in the particulate, and the OC/EC ratio can be associated with the source of the particulate. The parameters for burning wood and vegetation are described in Table 6.[2] Similar parameters for burning biomass are described in Table 7.[3, 4]

The OC/TC ratios in Table 6 indicated the surface particulate in the smoke-exposed houses was characteristic of burning wood or vegetation; and was not characteristic of particulate from vehicle emissions, cooking, etc. Second, the percent of EC in the particulate also indicated the probable source was biomass burning.

**Table 6. Particulate from burning wood and vegetation**

| Source | OC/TC Ratio | EC (%) |
|---|---|---|
| Vehicles (average) | 0.58 | - - |
| Coal Burning | 0.73 | 26% |
| Wood Burning (dry) | 0.81 | 12% |
| **Exposed Test Houses** | **0.82 – 0.89** | **14%** |
| Vegetation Burning | 0.93 | - - |
| Forest Fire (wet) | 0.94 | 3% |
| Charcoal Cooking | 0.95 | - - |

The OC/EC ratio in Table 7 was also consistent with a probable source of burning biomass. Therefore, it was concluded that the surface particulate in the smoke-exposed houses was probably indicative of residual wildfire contaminants.

**Table 7. Particulate from burning biomass**

| Source | OC/EC Ratio |
|---|---|
| **Exposed Test Houses** | **7.9** |
| Biomass Burning (Ref 3) | 7.8 ± 3 |
| Coal Burning (Ref 3) | 3.1 ± 0.6 |
| Fossil Fuel [Vehicles] (Ref 4) | 0.3 – 0.4 |

## 4.5 Wipe Samples: Total Carbon on Hard Surfaces

### 4.5.1 Elemental Carbon

Wipe samples were used to sample hard surfaces such as window sills, cabinets, dressers, door jambs, etc. The wipe samples were analyzed for Elemental Carbon, Organic Carbon, and Total Carbon [the sum of these two carbons] using the NIOSH 5040 Method. Elemental carbon is carbon particulate. Organic carbon, including primary and secondary organic aerosols (SOA) is partially oxidized fuel, and may include such chemical compounds as levoglucosans, diacids, aldehydes, pinenes, polynuclear aromatic hydrocarbons, methoxyphenols, etc.

The concentrations of EC in surface wipe samples was summarized in Table 8. The results were reported in units of micrograms per sample (ug/sample). Based on a comparison with the data from Group IV control houses, an EC concentration greater than 100 ug/sample was considered to be indicative of residual contamination. This value was arbitrarily selected as the highest concentration detected in a control house, but a third of the "exposed house" concentrations.

**Table 8. Concentration of Elemental Carbon in Hard-Surface Wipe Samples.**

| HOUSE | GROUP | ug/sample | CLASSIFICATION |
|---|---|---|---|
| 8 | IV | 19 | Not Elevated |
| 8 | IV | 33 | Not Elevated |
| 7 | IV | 100 | Not Elevated |
| 3 | II | 100 | Not Elevated |
| 2 | I | 280 | Elevated |
| 4 | II | 330 | Elevated |
| 1 | I | 350 | Elevated |
| 6 | III | 370 | Elevated |
| 5 | II | 1,038 | Elevated |

EC concentrations collected from hard surfaces using wipe samples indicated a difference between smoke-exposed houses and control houses, and could be used to assess the level of restoration. The EC concentrations in wipe samples collected from hard surfaces were illustrated in Figure 7. The two control houses had an average EC concentration of 75 micrograms (ug), the restored and owner-cleaned houses had an EC concentration of about 300 ug/sample, and the unrestored house had an average EC concentration of 1,400 ug/sample. Second, EC was 38% higher in the restored houses compared to the control houses. This result suggested the presence

of residual surface contaminants; and that the restoration protocols had probably not returned the houses to a pre-incident condition.

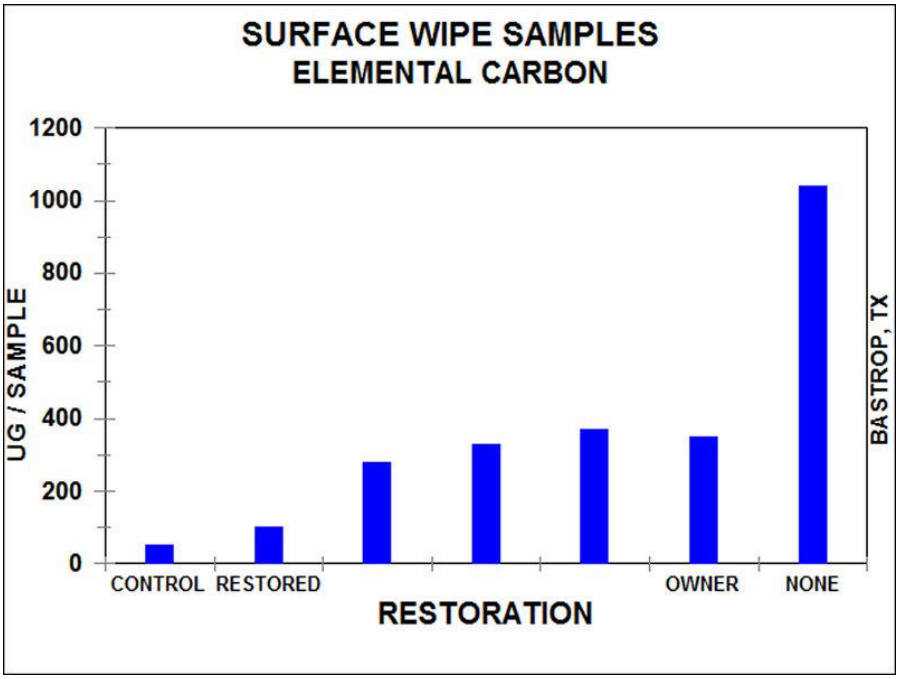



**Figure 7. Comparison of Elemental Carbon concentrations for levels of restoration.**

### 4.5.2 Organic Carbon

The concentrations of Organic Carbon in wipe samples were summarized in Table 9. The results were reported in units of micrograms per sample (ug/sample). Based on a comparison with the data from Group IV control houses, an OC concentration of 1,000 ug/sample or greater was considered to be indicative of residual contamination.

**Table 9. Concentrations of Organic Carbon in Wipe Samples (ug/sample).**

| HOUSE | GROUP | ug/sample | CLASSIFICATION |
|---|---|---|---|
| 8 | IV | 330 | Not Elevated |
| 8 | IV | 460 | Not Elevated |
| 7 | IV | 660 | Not Elevated |
| 3 | II | 940 | Moderately Elevated |
| 2 | I | 1,800 | Elevated |
| 4 | II | 2,100 | Elevated |
| 1 | I | 2,450 | Elevated |
| 6 | III | 2,700 | Elevated |
| 5 | II | 4,650 | Elevated |

Organic Carbon concentrations for wipe samples collected from hard surfaces indicated a difference between smoke-exposed houses and control houses, and could be used to assess the level of restoration, as illustrated in Figure 8.

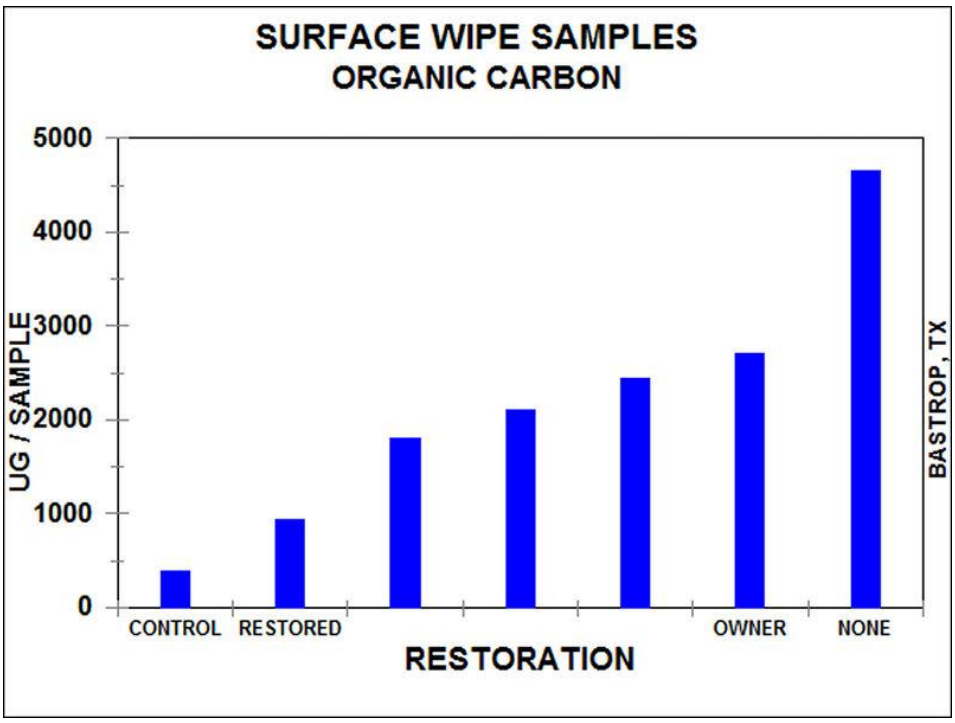



**Figure 8. Comparison of Organic Carbon concentrations for levels of restoration.**

The Elemental Carbon and Organic Carbon data in Tables 8 and 9 are presented as a log-plot in Figure 9.

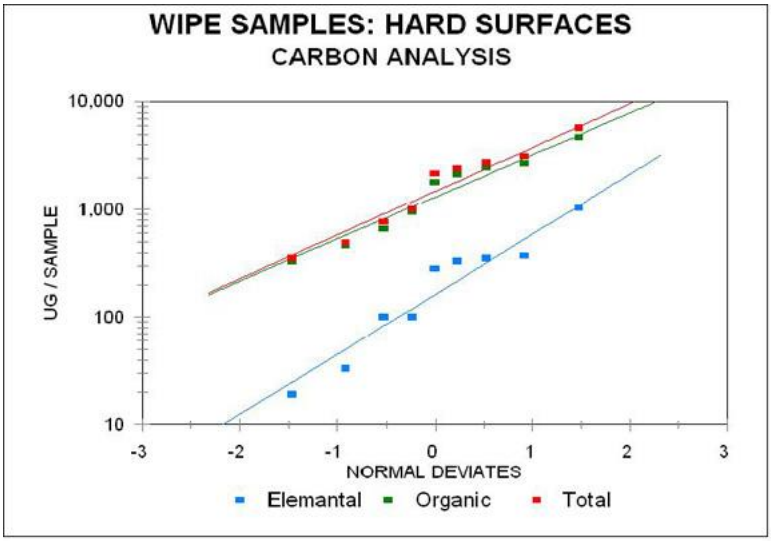



**Figure 9. Carbon Concentrations from Wipe Samples Collected from Hard Surfaces.**

## 4.6 Cassette Samples: Total Carbon on Soft Surfaces

Closed-face cassettes were used to sample soft-surface items (couches, bed spreads, etc.). The concentrations of EC in the cassette samples collected from soft surfaces were summarized in Table 10. The results were reported in units of micrograms per 100 square centimeters (ug/100 $cm^2$). EC concentrations indicated a difference between smoke-exposed houses. An EC concentration greater than 20 ug/100 $cm^2$ was considered to be indicative of residual contamination based on Figure 10.

**Table 10. Concentration of Elemental Carbon in Cassette Samples.**

| HOUSE | GROUP | Ug/100 $cm^2$ | CLASSIFICATION |
|---|---|---|---|
| 7 | IV | 10 | Not Elevated |
| 8 | IV | 10 | Not Elevated |
| 3 | II | 15 | Not Elevated |
| 2 | I | 16 | Not Elevated |
| 4 | II | 40 | Elevated |
| 1 | I | 41 | Elevated |
| 6 | III | 59 | Elevated |
| 5 | II | 64 | Elevated |
| 1 (Carpet) | Visible Spot | 360 | Contaminated |

The carpet in the master bedroom of House # 1 was darkly discolored at the rear entrance door. The discoloration appeared to be a soot-like substance, which was confirmed to be smoke residue by the sample results.

The concentrations of OC in cassette samples collected from soft surfaces were summarized in Table 11. The results were reported in units of micrograms per 100 square centimeters (ug/100 $cm^2$). An OC concentration greater than about 200 ug/100 $cm^2$ was considered to be indicative of residual contamination based on Figure 10.

**Table 11. Concentration of Organic Carbon in Cassette Samples (ug/100 $cm^2$).**

| PROPERTY | GROUP | AVERAGE | CLASSIFICATION |
|---|---|---|---|
| 3 | II | 97 | Not Elevated |
| 2 | I | 140 | Not Elevated |
| 4 | II | 180 | Not Elevated |
| 1 | I | 380 | Elevated |
| 6 | III | 420 | Elevated |
| 5 | II | 420 | Elevated |
| 1 Carpet | Visible Spot | 2,800 | Contaminated |

*Conclusion: Organic Carbon concentrations for cassette samples may have indicated a difference between smoke-exposed houses.*

The EC and OC data in Tables 10 and 11 were presented as log-plots in Figure 10.

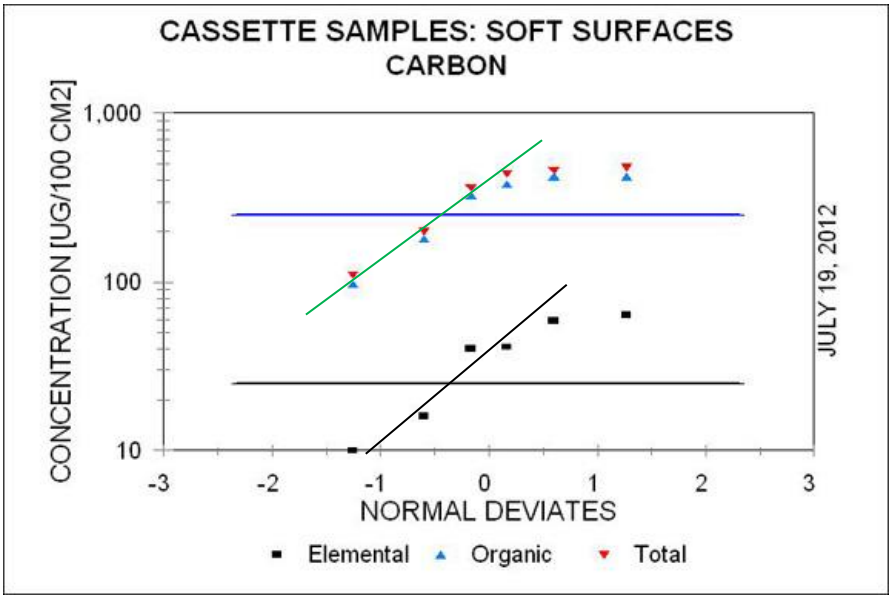



**Figure 10. Carbon Concentrations Collected from Soft Surfaces by Cassette Samples.**

## 4.7 Airborne Aldehydes

Sampling for airborne aldehyde concentrations was used to assess both hidden reservoirs of combustion products and occupant exposure potentials. Surface sampling was considered to be a suitable method for detecting wildfire contaminants that might be present on readily accessible surfaces. However, surface sampling was not considered to be suitable for assessing either hidden contaminant reservoirs or occupant exposure potential.

The continued reporting of occupant exposure post-restoration raised the possibility that accessible areas of the interior spaces had been cleaned and restored, but that hidden spaces may have escaped restoration. The detection of hidden reservoirs of combustion products was based on airborne aldehyde concentrations. Low molecular weight aldehydes are semi-volatile chemicals. If the source was combustion products, then the aldehydes would be expected to dissipate rapidly once the source was removed. For example, the half-life of acrolein in residential environments has been reported to be about 14 hours.[(5)] Since the samples were collected approximately eight months after the fire, and following restoration, detection of contaminant aldehydes at elevated concentrations was interpreted as an indication that hidden reservoirs of combustion products may still have been affecting the indoor environment.
Selecting assessment criteria that were associated with health effects, and for which exposure guidelines were available, was more difficult. Only acrolein and formaldehyde were associated with respiratory and sensory irritation; and had recommended exposure guidelines for residential

environments. Therefore, the assessment of occupant exposure was limited to these two contaminants.

### 4.7.1 Assessment Criteria for Airborne Aldehydes

Airborne samples collected using NIOSH Method 2016 were analyzed for the presence of 15 aldehydes; and the association of each aldehyde with the level of restoration was examined. An example of how these associations were assessed was illustrated in Figure 11 for acrolein. The first six samples were the smoke-exposed houses, samples 7 through 13 were the unexposed control houses, and sample 14 was an outdoor reference sample. One control house had medium density fiberboard trim (7-10), a potential source of formaldehyde, while the second control house had wood trim (11-13).

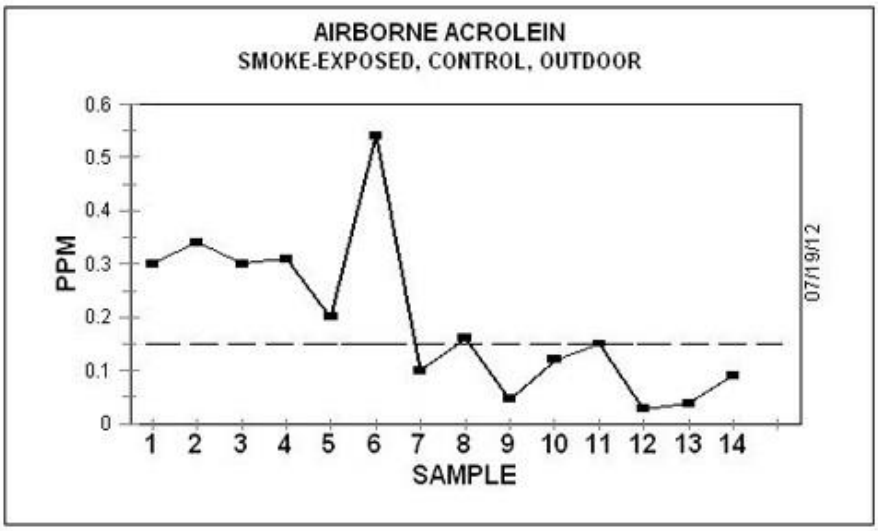



**Figure 11. Airborne Acrolein Concentrations**

Acrolein is an unsaturated aldehyde that is toxic, and is both a mucous-membrane and respiratory irritant. The acrolein concentrations in Figure 11 were all greater than 0.15 ppm in the smoke-exposed houses and less than that concentration in the unexposed houses. Therefore, an acrolein concentration greater than 0.15 ppm was assumed to be associated with the detection of residual wildfire contamination.

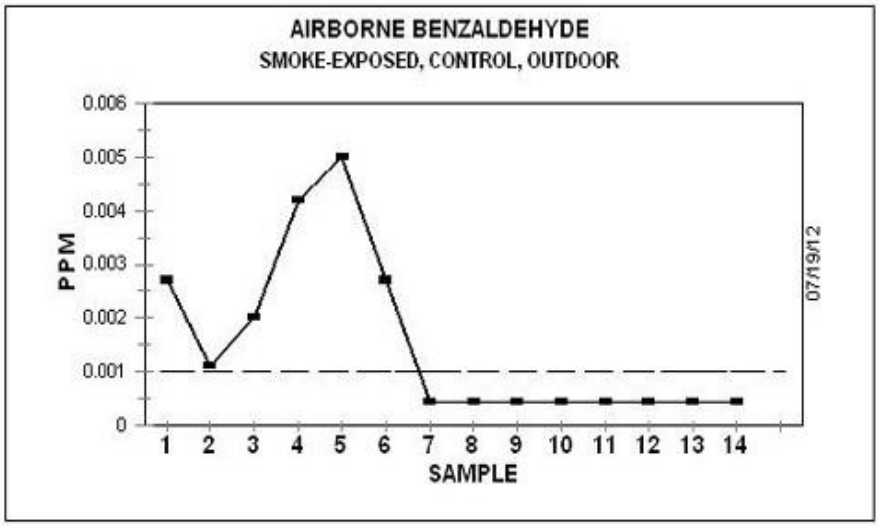



**Figure 12. Airborne Benzaldehyde Concentrations**

Benzaldehyde (Figure 12) was only detected in the smoke-exposed houses. The concentrations in both of the control houses and the outdoor reference sample were below the limit of detection. The smoke-exposed houses had benzaldehyde concentrations greater than 0.001 ppm.

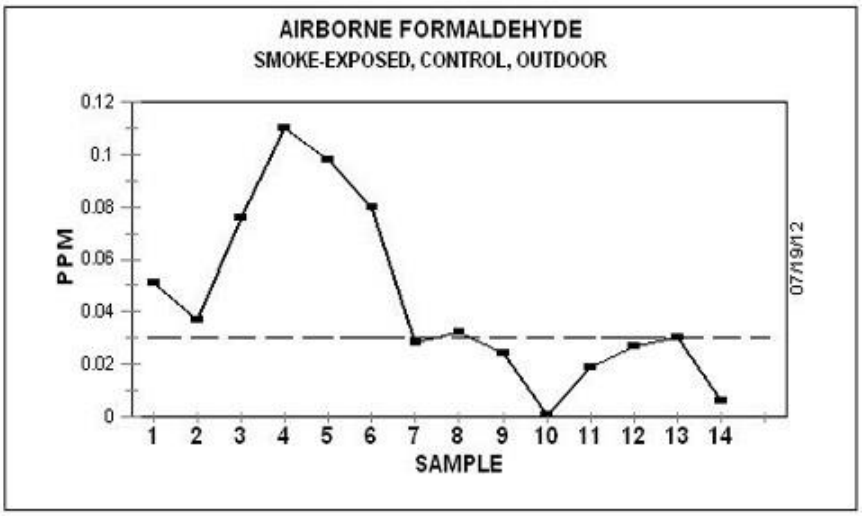



**Figure 13. Airborne Formaldehyde Concentrations**

Formaldehyde (Figure 13) is toxic and can be both a mucous-membrane and respiratory irritant. The six smoke-exposed houses all had concentrations exceeding 0.03 ppm, while the control houses were all below this concentration.

Acrolein, benzaldehyde, and formaldehyde accounted for78% of the 15 aldehydes that were included in the analysis. In addition, they were the only aldehydes that completely differentiated between the six smoke-exposed houses and the two unexposed control houses.

These three aldehydes could be used to discriminate between smoke-exposed and unexposed houses. The log-plots for these three aldehydes were illustrated in Figure 14. All three aldehydes had similar geometric standard deviation values (1.4, 1.5, and 1.7, respectively). The low values for the GSD and narrow ranges suggested a common source for these aldehydes; presumably the subject "Bastrop" wildfire.

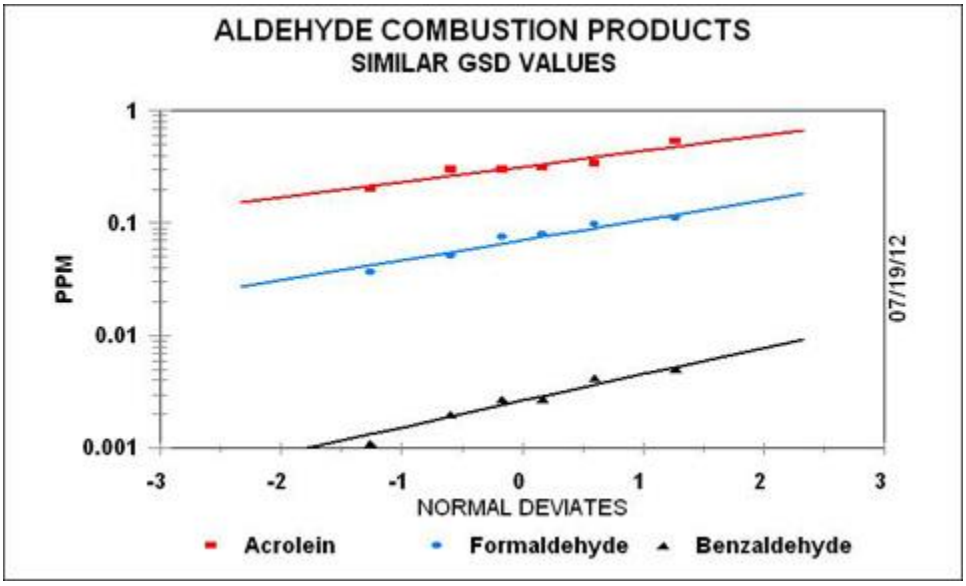



**Figure 14. Aldehydes with Similar Geometric Standard Deviations (GSD).**

The log-plots for the concentrations of the three aldehydes detected in the six smoke-exposed houses and the two control houses were illustrated in Figure 15. The horizontal lines indicate the concentrations denoting contaminated and uncontaminated indoor environments discussed in the Appendix: Toxicity Data. It was expected from Figure 15 that more than half the occupant exposures in the six houses would exceed the recommended residential limits for acrolein and formaldehyde. In addition, acrolein, benzaldehyde, and formaldehyde were good indicators of hidden contaminants that may be off-gassing from residual wildfire contaminants.

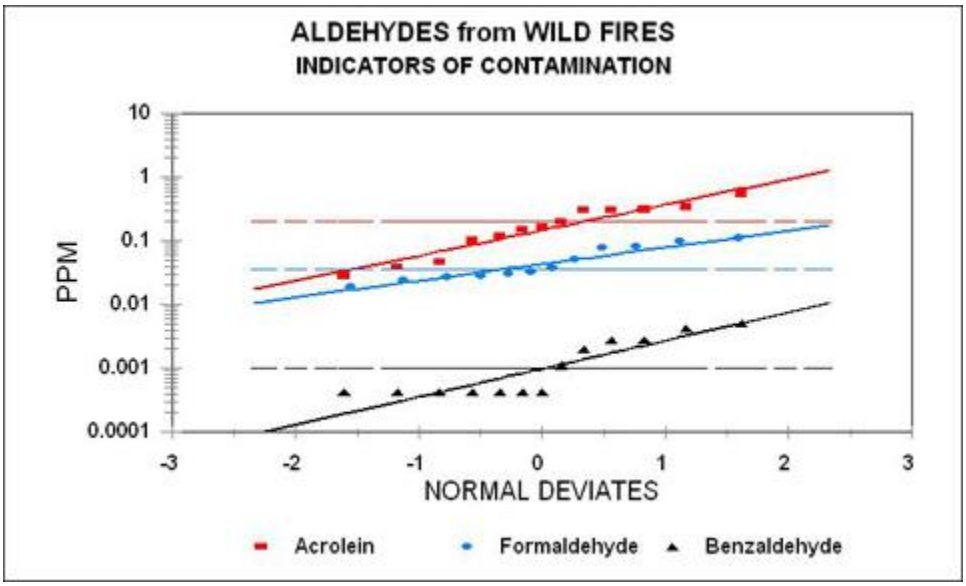



**Figure 15. Three Aldehydes with their Limit Concentrations Indicated.**

## 5.0 APPENDIX: TOXICITY DATA

Guidelines for residential exposures to selected chemicals are available in Toxicological Profiles published by USPHS/CDC/ATSDR.[6, 7] Occupant exposure potentials were assessed by comparing the concentrations of acrolein and formaldehyde with the CDC/ATSDR exposure guidelines for residential environments listed in Table 12. The guidelines refer to acute (14 days or less), intermediate (15 – 364 days), and chronic (365 days or more) exposure periods.

**Table 12. CDC/ATSDR MRL exposure guidelines for residential environments (ppb)**

| Aldehyde | Acute | Intermediate | Chronic |
|---|---|---|---|
| Acrolein | 3 | 0.04 | NA |
| Formaldehyde | 40 | 30 | 8 |

REL: EPA Recommended Exposure Level (parts per billion)
MRL: ATSDR Minimal Risk Level (parts per billion)
CDC: Centers for Disease Control and Prevention
ATSDR: Agency for Toxic Substance and Disease Registry

### 5.1 Toxicological Profile for Acrolein

**Table 13. Concentrations of Acrolein in Parts per Million by Volume (ppm).**

| HOUSE | 1 | 2 | 3 | 5 | 4 | 6 | 7* | 8* |
|---|---|---|---|---|---|---|---|---|
| Acrolein (ppm) | 0.3000 | 0.3400 | 0.3000 | 0.3100 | 0.2000 | 0.5400 | 0.1300 | 0.1053 |
| Ratio: Controls* | 2.5 | 2.8 | 2.5 | 2.6 | 1.7 | 4.5 | 1.1 | 0.9 |

*Conclusion: The concentration of acrolein was substantially elevated in all six smoke-exposed houses compared to concentrations in control houses.*

Acrolein is a potent irritant to the mucous membranes. The nasal tissues appear to be the most sensitive target of inhalation exposure, with onset of noticeable irritation occurring in seconds at a concentration of 0.3 ppm. The eyes also rapidly become irritated at a concentration of 0.3 ppm. The concentration of acrolein equaled or exceeded 0.3 ppm in five of the six houses – and this was a substantial period after the subject incident.

Also, acrolein that enters the air as a vapor changes into other chemicals within days. Therefore, there appears to have been a continuing emission source in the six houses since the fire had occurred some time prior to the sampling.

Estimates of exposure levels posing minimal risk to humans (MRLs) have been made for acrolein by CDC/ATSDR. An MRL is defined as an estimate of daily human exposure to a substance that is likely to be without an appreciable risk of (noncarcinogenic) adverse effects over a specified duration of exposure.

MRLs are based on noncancerous health effects only and do not consider carcinogenic effects. MRLs are typically calculated for acute (14 days or less), intermediate (15-364 days), and chronic (365 days or more) exposures.

An MRL of 0.003 ppm has been derived for acute-duration inhalation exposure (14 days or less) to acrolein. A concentration of 0.3 ppm is 100-times this exposure limit, with measured concentrations ranging from 67-times to 180-times this exposure limit.

An MRL of 0.00004 ppm has been derived for intermediate-duration inhalation exposure (15–364 days) to acrolein. A concentration of 0.3 ppm is 7,500-times this exposure limit, with measured concentrations ranging from 5,000-times to 13,500-times this exposure limit.

## 5.2 Toxicological Profile for Formaldehyde

**Table 14. Concentrations of Formaldehyde in Parts per Million by Volume (ppm).**

| PROPERTY | 1 | 2 | 3 | 5 | 4 | 6 | 7* | 8* |
|---|---|---|---|---|---|---|---|---|
| Formaldehyde | 0.051 | 0.037 | 0.076 | 0.11 | 0.098 | 0.080 | 0.030 | 0.014 |
| Ratio: Controls* | 2.3 | 1.7 | 3.5 | 5.7 | 4.5 | 3.6 | 1.4 | 0.6 |

*Conclusion: The concentration of formaldehyde was substantially elevated in five of the six smoke-exposed houses compared to concentrations in control houses.*

An MRL of 0.04 ppm has been derived for acute-duration inhalation exposure (14 days or less) to formaldehyde.

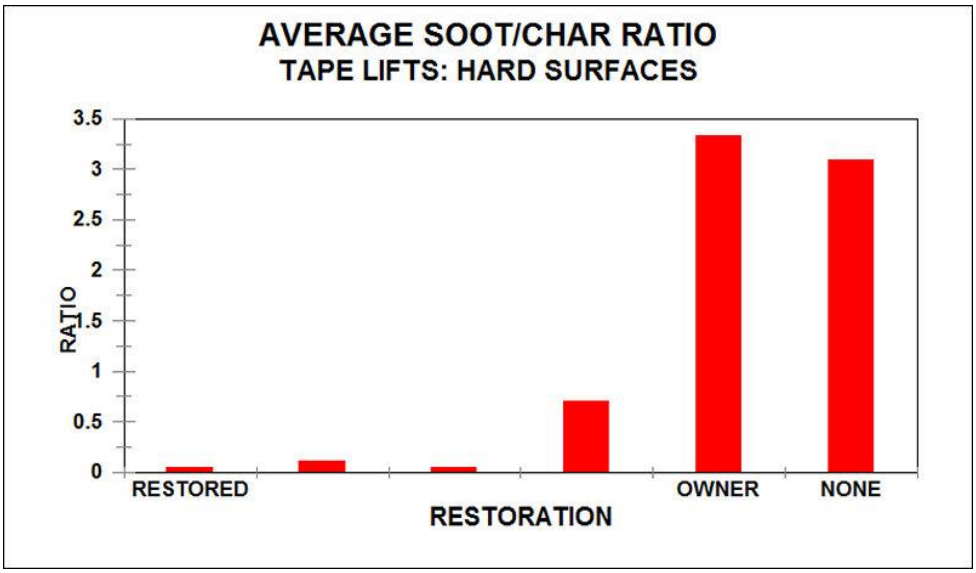
An MRL of 0.03 ppm has been derived for intermediate-duration inhalation exposure (15–364 days) to formaldehyde.

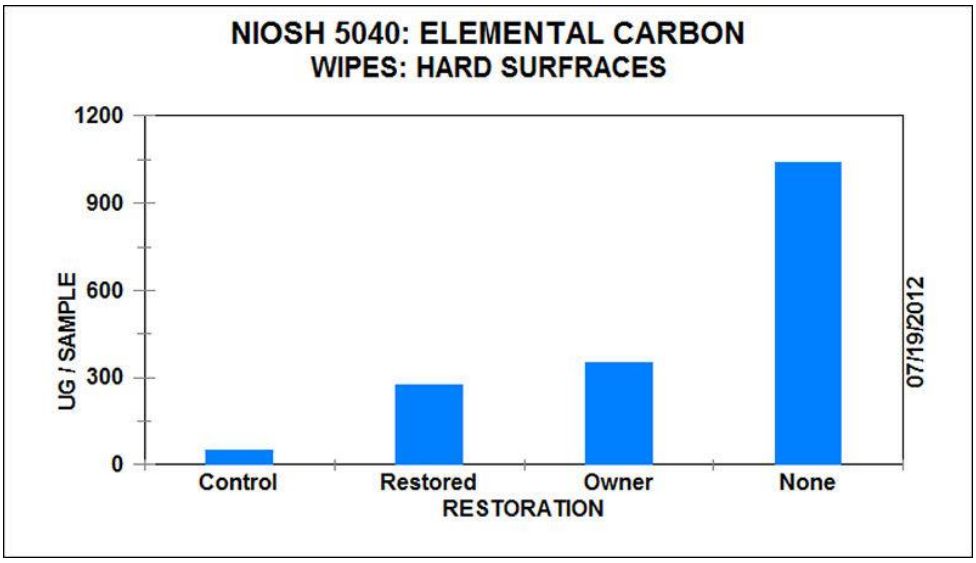
An MRL of 0.008 ppm has been derived for chronic-duration inhalation exposure (365 days or more) to formaldehyde.

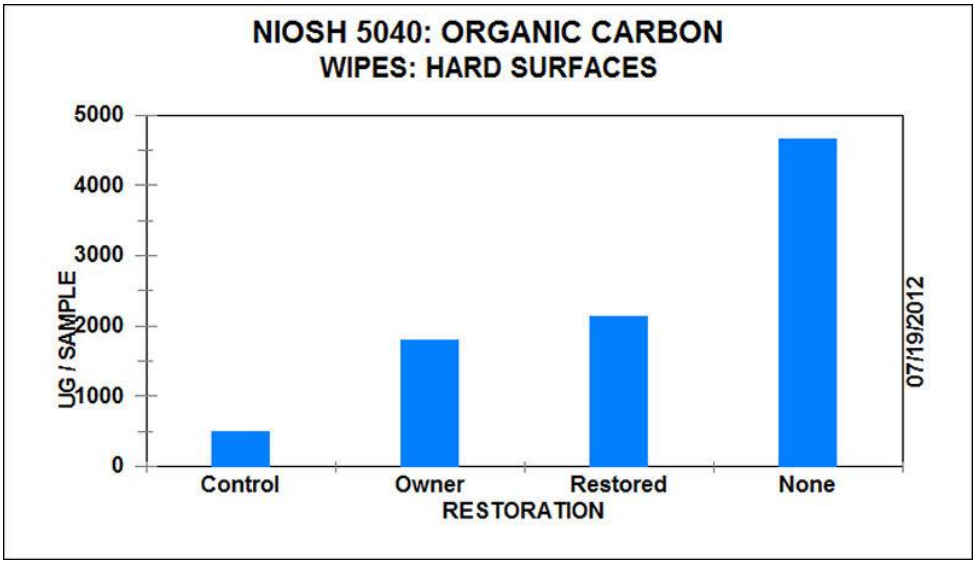
### 5.3 Occupant Exposure Potential

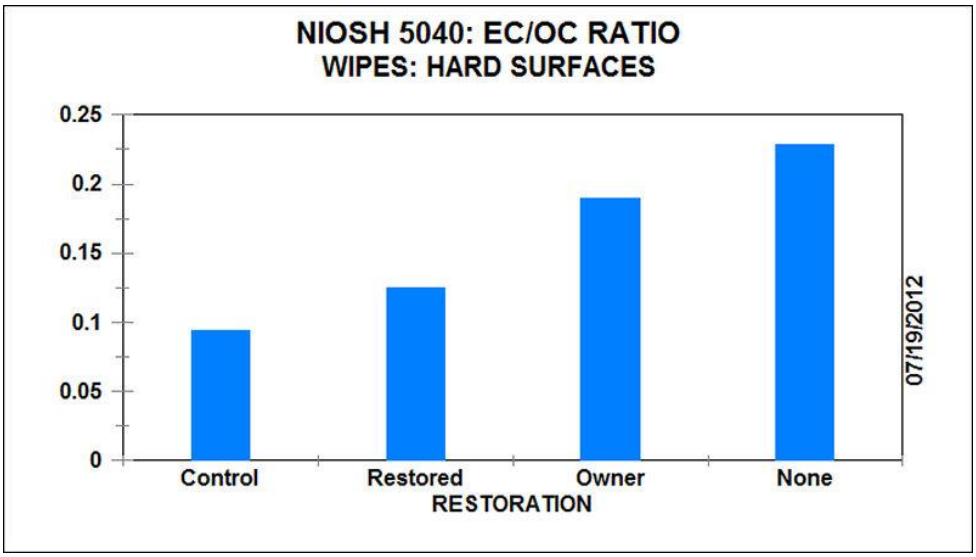
The airborne results indicated that the concentrations of acrolein and formaldehyde exceeded the acute MRL's in all six post-restoration houses. The factors by which the concentrations exceeded the acute MRL ranged from 13 to 38 for acrolein and from 5 to 13 for formaldehyde. In addition, the median concentration of acrolein in the six houses was 100-times greater than the median concentration in typical residential environments.[6] It was concluded that residual aldehyde concentrations were consistent with the reporting of adverse health effects by occupants.

## 6.0 Indicators of Wildfire Contamination




NIOSH 5040: ELEMENTAL CARBON
WIPES: HARD SURFRACES
1200
900
600
300
0
UG / SAMPLE
Control
Restored
Owner
None
RESTORATION
07/19/2012


NIOSH 5040: ORGANIC CARBON
WIPES: HARD SURFACES
5000
4000
3000
2000
1000
0
UG / SAMPLE
Control
Owner
Restored
None
RESTORATION
07/19/2012



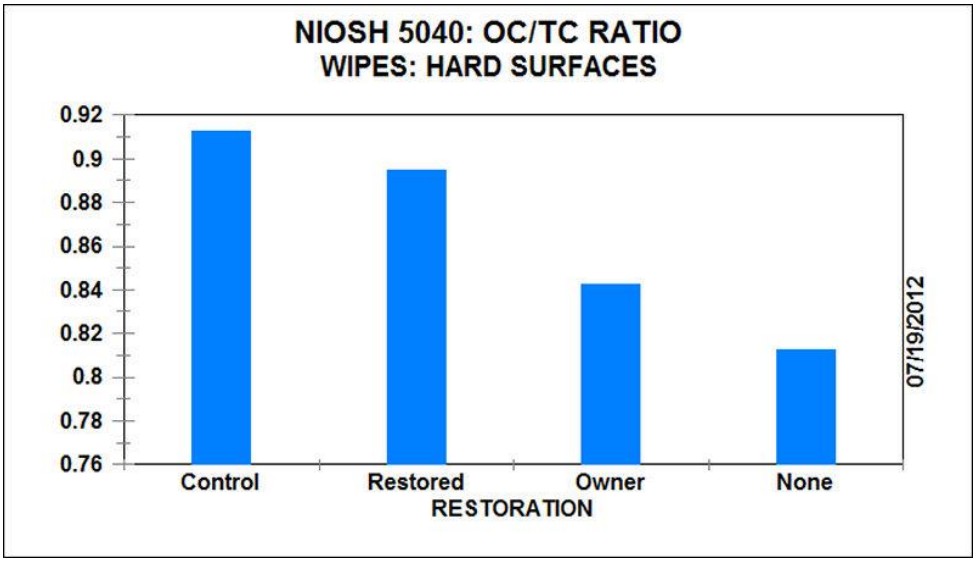




**Table 15. Average EC and OC concentrations on hard surfaces by wipe samples (ug/sample)**

| Contaminant | Elemental Carbon | Organic Carbon | Acceptance Criteria |
|---|---|---|---|
| Control Houses | 100 ug | 1,000 ug | Less than 300 ug |
| Exposed Houses | 300 ug | 2,000 ug | Less than 2,500 ug |

**Table 16. PRV criteria for airborne aldehydes in restored houses**

| Aldehyde | Maximum "Control" Concentration |
|---|---|
| Sum of Concentrations | Less than 0.20 ppm |
| Acrolein | Less than 0.15 ppm |
| Formaldehyde | Less than 0.03 ppm |
| Benzaldehyde | Less than 0.001 ppm |

## CONCLUSIONS

Concentrations of EC and OC collected using the NIOSH 5040 Method were associated with the level of restoration. The establishment of decision criteria for assessing the level of restoration appeared to be feasible.

Both surface carbon and airborne aldehyde concentrations were higher in restored houses compared to control houses, suggesting that the restoration protocols applied to the test houses were not sufficiently effective to return the houses to a pre-incident condition.

The post-restoration houses represented a chronic exposure hazard to the occupants based on a comparison of acrolein and formaldehyde concentrations with CDC/ATSDR guidelines for residential environments.

The quantitative, standardized, and validated NIOSH 5040 Method (total carbon) and NIOSH 2016 Method (aldehydes) were useful for assessing the condition of post-restoration smoke-exposed houses.

## LIMITATIONS

The study reported in this article was performed as part of a legal case. Therefore, it was a limited field study and not a controlled study. The site visits were performed eight-months post-incident, so it was neither possible to control for, nor verify, variations in contractors, restoration techniques, cleaning methods, etc. How these variables were applied to each property is an unknown. Second, only a limited amount of time was spent in each house, and the occupants were sometimes not present to be interviewed. The actual extents of restoration, the restoration techniques, and the diligence with which cleaning methods were applied remain unknowns. Many of the conclusions reported in the study are independent of these factors. However, these uncertainties and limitations did not prevent useful conclusions from being attained.

Even with these limitations, several areas for future research were identified. EC and OC ratios had a demonstrated utility for assessing sources such as coal, vehicles, and vegetation; but can surface carbon be broadly applied to identifying wildfires as the source of contaminants? What is the “true” transition point for those ratios between uncontaminated and contaminated? What are the “standard” methods that can be applied to wildfire investigations? Can they be validated in stratified field studies? How does their utility for assessing condition compare to the use of validated NIOSH methods?

Finally, concentrations of acrolein and formaldehyde in the six restored houses substantially exceeded the CDC/ATSDR guidelines for residential environments. Exposure guidelines intended to protect people may be referred to as primary guidelines, while those intended to protect property may be designated as secondary guidelines. The results of this limited study suggest that the six restorations met secondary guidelines, but fell woefully short of meeting

primary guidelines. Should occupant protection be a recognized goal of [wild]fire restoration? Should the restoration contractor state whether the objective of the restoration is to meet primary or secondary guidelines? Other than acrolein and formaldehyde, what are those guidelines?

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5. Seaman, V., Bennett, D., Cahill, T. Indoor acrolein emission and decay rates resulting from domestic cooking events. Atmospheric Environment, 43(39): 6199-6204, 2009.

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7. Toxicological Profiles for Formaldehyde, US Dept. of Health and Human Services, Public Health Service, 1999. [CDC/ATSDR]