Post-Restoration Verification Sampling of Wildfire Smoke Contaminants

>> by Joe C. Spurgeon, Ph.D.

Introduction

Six houses that had been exposed to wildfire smoke contaminants and then professionally restored were sampled for the presence of residual smoke-related contaminants. The study was performed because the occupants of the houses exposed to wildfire smoke were still reporting the symptoms in Table 1 eight months after the wildfire. Importantly, the symptoms persisted even eight-months after the houses had been professionally restored.

The study was conducted to determine if residual wildfire contaminants were 1) still present in the houses, 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.
- Sampling methods capable of detecting those contaminants.
- The source of contaminants (cooking or wildfire).
- A decision logic for associating contaminants with the level of restoration.
- Post-restoration acceptance criteria for assessing the structure and occupant exposure.

Assessment Strategy

A stratified sampling strategy was used in the study, in which the test houses were stratified (separated) by their reported condition. The conditions of the eight houses included in the study are described in Table 2. The houses were ranked in the table by the expected extent of contamination, increasing from low (controls) to high (unrestored).

The eight houses were grouped into four categories: controls (2), professional restoration (4), owner restoration (1), and no restoration (1). The grouping of the houses allowed a series of questions to be addressed:

1. Was a sampling method capable of assigning a house to one of the four categories?
2. Did contaminant concentrations differ between the four categories of restoration?
3. Was there a difference in condition between professional and owner restoration?
4. Had the restoration protocols been effective in controlling occupant exposure?

Implementing the assessment strategy included the following steps:

1. Select houses stratified by condition.
2. Identify contaminants and sampling methods.
3. Identify parameters associated with condition.
4. Assess the ability of a method to differentiate between condition,
   a. Building related.
   b. Human related.

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

Table 1. Prevalence of Occupant Health Symptoms

5. Establish objective guidelines for assessing condition and occupant exposure.

Methods

The contaminants and sampling methods included in the study arre listed in Table 3. The NIOSH (National Institute for Occupational Safety and Health) sampling methods were selected because they were quantitative, standardized, validated and could be applied in a consistent manner.

NIOSH Method 5040. Combustion particulate was collected on a 37-milimeter (mm) glass fiber filter that had been heat treated to 700ºC to remove organic binders. Since binders had been removed, the filter was easily degraded by rough surfaces. A circular area of 1.5 centimeter $(cm)^2$ was punched out of the center of the 10.8 cm^2 filter by the laboratory and analyzed for elemental carbon (EC), organic carbon (OC), and total carbon (TC = EC + OC) using evolved gas analysis (EGA). Sample media and analyzes were provided by ALS Environmental, Salt Lake City, UT.

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 four 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

Test Houses	Number
Controls (not exposed, occupied)	2
Restored (occupied)	2
Restored (furniture steam cleaned)	1
Restored (and remodeled, occupied)	1
Cleaned by Owner (occupied)	1
Unrestored (unoccupied)	1

Table 2. Descriptions of restoration for the eight test houses.

Synopsis

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

Tape lift samples were collected to measure the percentage of soot and char by light microscopy. The percentage of soot varied from less than 10 percent in restored houses to greater than 40 percent in the owner-restored and unrestored houses. The percentage of char varied in a comparatively narrow range between 10 and 15 percent and was less useful in characterizing the condition of a surface.

Surface contamination was 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, while micro-vacuum cassette samples were collected on soft-surfaces using an area template. The concentrations of EC and OC on hard surfaces were associated with the descriptions of restoration. Carbon concentrations collected from soft surfaces were not clearly associated with those descriptions.

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 control houses. The concentrations of the three aldehydes were useful as indicators of hidden contaminants and for assessing occupant exposures. Occupant exposures to acrolein and formaldehyde were elevated relative to residential exposure guidelines even eight months after the fire, and the concentrations were consistent with the reported symptoms of respiratory distress and eye irritation.

Study Limitations

The study was performed as part of a legal case. Thus 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.

A limited amount of time was spent in each house, and the occupants were sometimes not present to be interviewed. The actual extent 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 are limitations for those conclusions that may be influenced by these factors.

Several areas for future research were identified. Why were surface contaminants on hard surfaces associated with the perceived extent of restoration but not on soft surfaces? Is it cost-effective to restore soft surfaces? EC and OC ratios have a demonstrated utility for assessing sources such as coal, vehicles, and vegetation; but can surface carbon be broadly applied to properties affected by wildfire contaminants? What is the range of those ratios? What are the "standard" methods that can be applied to wildfire investigations? Can they be validated in stratified field studies?

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 noticeably 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?

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 two-piece 37-mm cassette at an airflow rate of 10 liters per minute (lpm). A 10 cm × 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).

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 [0–500 cc/min air sampling pumps are available commercially]. 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).

Results and Discussion

The goal of the study was to develop a post-remediation verification (PRV) method suitable for detecting the presence of wildfire contaminants. The study was limited to four objectives:

1. Select one or more contaminants that could be associated with wildfire smoke.
2. Select a sampling/analytical method that had been validated, with known characteristics.
3. Verify a rank order between the selected contaminants and reported condition of houses.
4. Establish a decision logic for objectively assessing the condition of the test houses.

Combustion products are a complex mixture of gases, vapors and particulates. However, the contaminants included in the study were limited to surface soot and char, surface total carbon, and airborne aldehydes. These simple, relatively cost-effective parameters were associated with the presence of residual post-remediation combustion products.

Char and Soot. The percentages of soot and char on hard surfaces were measured in the six smoke-exposed houses by collecting tape lift samples and analyzing them by polarized light microscopy.[1] This was a simple, cost-effective method for detecting contaminants on accessible surfaces. However, the method was considered to be semi-quantitative. In addition, surface sampling was not a suitable method for detecting hidden contaminant reservoirs or assessing occupant exposure.

IESO (Indoor Environmental Standards Organization) Standard 6001-2012 specifies the percent of char (%-char) as a primary indicator of surface combustion particulate in HVAC systems. Figure 1 describes the association between %-char on hard surfaces and condition. The %-char was less than 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 suggested it may be a poor indicator of condition.

IESO Standard 6001-2012 also specifies the percent of soot (%-soot) as a secondary indicator of surface combustion particulate in HVAC systems. Figure 2 describes the association between %-soot on hard surfaces and condition. 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.

It was concluded that %-soot was associated with condition in these six samples. In addition, 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 much more effective in removing soot from hard surfaces.

Total, Elemental and Organic Carbon. The concentrations of elemental carbon (EC), organic carbon (OC), and total carbon (TC) were also measured on accessible surfaces in the eight test houses. Wipe samples were used to sample hard surfaces, and cassette samples were used to sample soft surfaces. Since the NIOSH 5040 Method is a quantitative, standardized method, these data provided a better opportunity to assess associations

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

Table 3. Contaminants and sampling methods

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	- -

Table 4. Particulate from burning wood and vegetation

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
Vegetation Burning	0.93
Forest Fire (wet)	0.94
Charcoal Cooking	0.95

Table 5. Particulate from burning biomass

between contaminant concentrations and condition.

Source of Particulate. The next step was to determine the probable source of any surface particulate that were detected. This was based on the concentrations of TC, OC and EC detected on accessible surfaces. 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 4.[2] Similar parameters for burning biomass are described in Table 5.[3, 4]

The OC/TC ratios in Table 4 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. Second, the percent of EC in the particulate also indicated the probable source was wood burning. The OC/EC ratio in Table 5 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.

Hard Surface Wipe Samples. The EC and OC concentrations in wipe samples collected from hard surfaces are illustrated in Figure 3 and Figure 4, respectively.

The concentration of EC was associated with the extent of restoration. For example, 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.

The concentration of EC was about 25 percent higher in the owner-cleaned

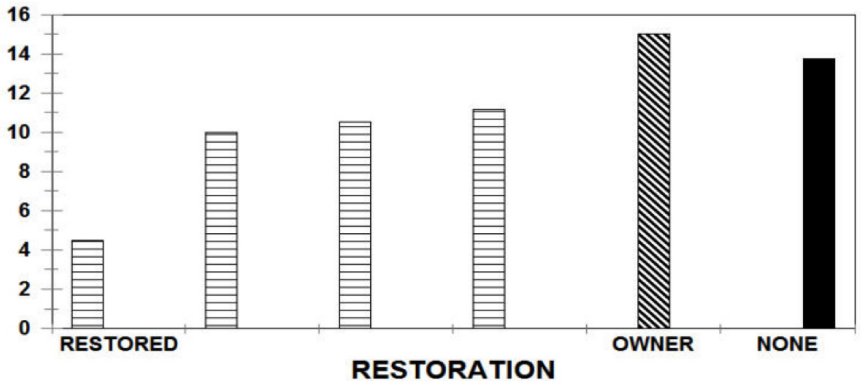

Figure 1. Percent char on hard surfaces by tape lift

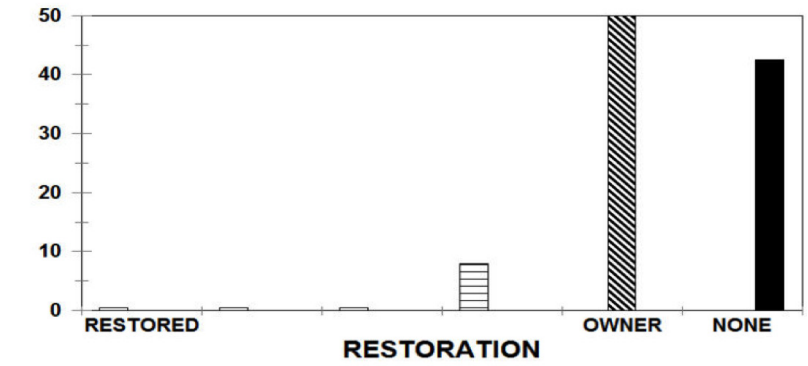

Figure 2. Percent soot on hard surfaces by tape lift

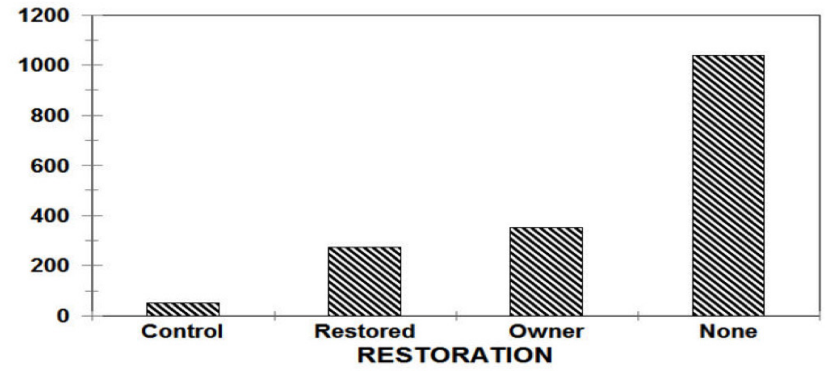

Figure 3. Comparison of elemental carbon concentrations by condition

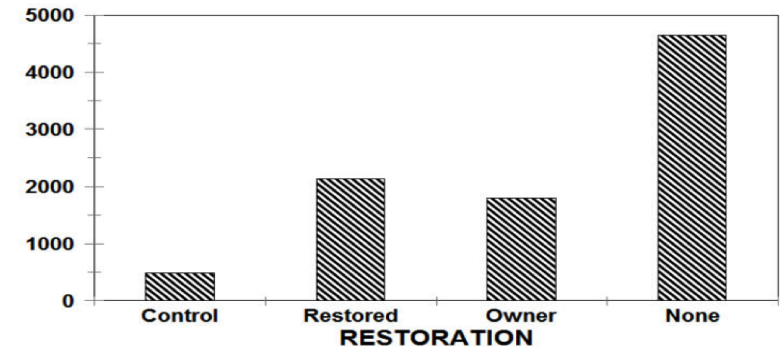

Figure 4. Comparison of organic carbon concentrations by condition

house compared to the average for the restored houses. In comparison, the OC concentration was higher in the professionally cleaned houses, as indicated in Figure 4. Therefore, the benefit derived from professional cleaning was not clear. However, elemental carbon has an IARC (International Agency for Research on Cancer) 2B classification (possible human carcinogen). In addition, many of the chemicals associated with organic carbon (polynuclear aromatics, for example) are known to be carcinogenic and/or mutagenic. Therefore, home owners should not be encouraged to clean areas potentially contaminated with combustion products.

Soft Surface Cassette Samples. The EC and OC concentrations detected by cassette samples collected from soft-surface items were not associated with condition. Wipe samples allowed the surface dust to be collected entirely on the center portion of the filter, which was the area punched out for analysis. However, the dust collected by cassette samples was distributed over the surface of the filter, although only the center of the filter was analyzed. This factor may have increased the variability of the soft-surface data collected by cassette. However, the reason for the lack of association with condition was not determined.

Airborne Aldehydes. 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 volatile chemicals. If the source was combustion products, then they 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 after restoration, detection of contaminant aldehydes was considered to be an indication that hidden reservoirs of combustion products were still 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 consensus exposure guidelines for residential environments. Therefore, the assessment of occupant exposure was limited to these two contaminants.

Airborne samples collected using NIOSH Method 2016 were analyzed for the presence of 15 aldehydes; and the association of each aldehyde with the extent of restoration was examined. An example of how these associations were assessed is illustrated for acrolein in Figure 5. 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), while the second control house had wood trim (11–13).

The acrolein concentrations in Figure 5 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.

The graph of formaldehyde concentrations had a similar appearance as acrolein, but the smoke-exposed and control houses were differentiated by a concentration of 0.03 ppm. In contrast, benzaldehyde was only detected in the

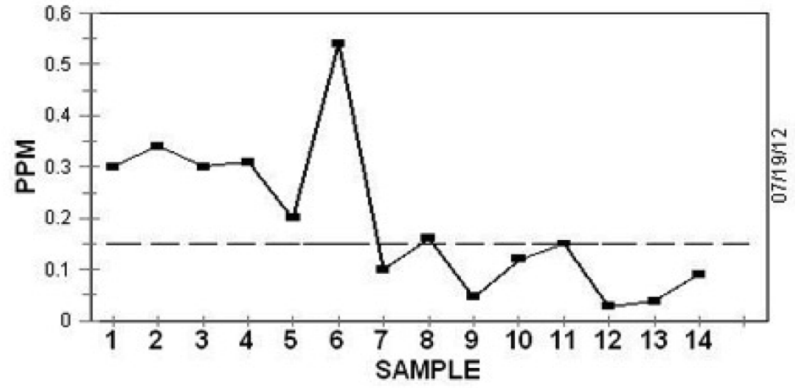

Figure 5. Acrolein concentrations in smoke-exposed and unexposed houses.

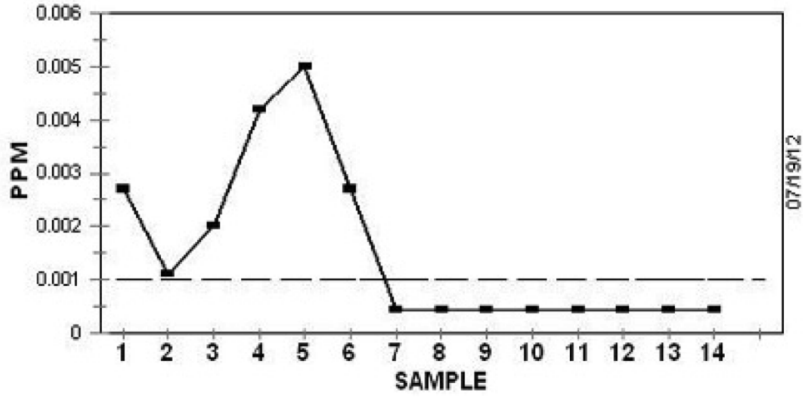

Figure 6. Benzaldehyde concentrations in smoke-exposed and unexposed houses.

smoke-exposed houses, as illustrated in Figure 6. The smoke-exposed and control houses were differentiated by a benzaldehyde concentration of 0.001 ppm.

Acrolein, benzaldehyde, and formaldehyde accounted for 78% of the 15 aldehydes that were included in the analysis. In addition, they were the only aldehydes that differentiated between the six smoke-exposed houses and the two unexposed control houses, as illustrated in Figure 5 and Figure 6.

Occupant Exposure Potential. Guidelines for residential exposures to selected chemicals are available in Toxicological Profiles published by 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 6. The guidelines refer to acute (14 days or less), intermediate (15-364 days), and chronic (365 days or more) exposure periods.

The post-restoration concentrations of acrolein and formaldehyde detected in the test houses are listed in Table 7.

The results in Table 7 indicate that the concentrations of acrolein and formaldehyde exceeded the acute MRLs 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.

PRV Acceptance Criteria. It was concluded that the concentrations of EC and OC in surface dust samples were an indication of residual wildfire contamination. The PRV criteria in Table 8 were derived from an examination of the data in Figure 3 and Figure 4. The two control houses had an EC concentration less than 100 ug/sample on surfaces, and an OC concentration less than 1,000 ug/sample. In comparison, the professionally restored houses had an average EC concentration of about 300 ug/sample, and an average OC concentration of about 2,000 ug/sample.

Airborne concentrations of acrolein, benzaldehyde, and formaldehyde were useful indicators of hidden contaminant reservoirs. Post-restoration verification criteria, in units of parts per billion (ppb), are listed in Table 9. In addition, the sum of the three concentrations was also a useful parameter for assessing contamination. For example, reasonable estimates of "acceptable" and "unacceptable" conditions were sums of less than 200 ppb and greater than 400 ppb, respectively.

Conclusions

Concentrations of EC and OC detected on hard surfaces using wipe samples and the NIOSH 5040 Method were associated with the extent of restoration. The establishment of decision criteria for assessing condition appeared to be feasible.

Concentrations of EC and OC detected on soft surfaces using microvacuum cassettes were not associated with the extent of restoration.

Both surface carbon and airborne aldehyde concentrations were higher in restored houses compared to control

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

Table 6. CDC/ATSDR MRL exposure guidelines for residential environments (ppb)

House	CDC	1	2	3	4	5	6
Cleaning	MRL	Prof	Prof	Prof	Prof	Owner	None
Acrolein	3	50	38	78	115	100	80
Formaldehyde	40	200	300	300	310	340	540

Table 7. Occupant exposure potentials for acrolein and formaldehyde (ppb)

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

Aldehyde	Maximum "Control" Concentration
Sum of Concentrations	Less than 200 ppb
Acrolein	Less than 150 ppb
Formaldehyde	Less than 30 ppb
Benzaldehyde	Less than 1 ppb

Table 9. PRV criteria for airborne aldehydes in restored houses

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 2016 Method (aldehydes) were useful for assessing the condition of post-restoration smoke-exposed houses.

Study 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 extent 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 are limitations for those conclusions that may be influenced by these factors.

Even with these limitations, several areas for future research were identified. First, why were surface contaminants on hard surfaces associated with the perceived extent of restoration but not on soft surfaces? Is it cost-effective to restore soft surfaces? Second, EC and OC ratios have a demonstrated utility for assessing sources such as coal, vehicles, and vegetation; but can surface carbon be broadly applied to properties affected by wildfire contaminants? What is the range of those ratios? Third, what are the "standard" methods that can be applied to wildfire investigations? Can they be validated in stratified field studies?

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 noticeably 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?

REFERENCES

1. Fields, James. Texas Smoke Detection Services, Houston, TX.
2. Chow, J., Watson, J. "Guideline on Speciated Particulate Monitoring"; US EPA, RTP, 1998.
3. Kirpa, R., Sarin, M.M. "Spatio-temporal variability in atmospheric abundances of EC, OC and WSOC over Northern India"; *Journal of Aerosol Science,* 41(1):88-98, 2010.
4. Casimiro, P., et al. "OC/EC ratio observations in Europe: Re-thinking the approach for apportionment between primary and secondary organic carbon"; *Atmospheric Environment,* 45(34):6121-6132, 2011.
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.
6. "Toxicological Profiles for Acrolein"; US Dept. of Health and Human Services, Public Health Service, 2007. [CDC/ATSDR]
7. "Toxicological Profiles for Formaldehyde"; US Dept. of Health and Human Services, Public Health Service, 1999. [CDC/ATSDR]

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