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Airborne contamination during post-fire investigations: hot, warm & cold scenes

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Abstract

Fire investigators may be occupationally exposed to many of the same compounds as the more widely studied fire suppression members of the fire service but are often tasked with working in a given exposure for longer periods ranging from hours to multiple days and may do so with limited personal protective equipment. In this study, we characterize the area air concentrations of contaminants during post-fire investigation of controlled residential fires with furnishings common to current bedroom, kitchen and living room fires in the United States. Area air sampling was conducted during different investigation phases including when investigations might be conducted immediately after fire suppression and extended out to 5-days after the fire.

Airborne particulate over a wide range of dimensions, including sub-micron particles, were elevated to potentially unhealthy levels (based on air quality index) when averaged over a 60 minute investigation period shortly after fire suppression with median PM2.5 levels over 100 μg/m^3 (range 16–498 μg/m^3) and median peak transient concentrations of 1,090 μg/m^3 (range 200–23,700 μg/m^3) during drywall removal or shoveling activities. Additionally, airborne aldehyde concentrations were elevated compared to volatile organic compounds with peak values of formaldehyde exceeding NIOSH ceiling limits during the earliest investigation periods (median 356 μg/m^3, range: 140–775 μg/m^3) and occasionally 1 day post-fire when the structure was boarded up before subsequent investigation activities.

These results highlight the need to protect investigators' airways from particulates when fire investigation activities are conducted as well as during post-fire reconstruction activities. Additionally, vapor protection from formaldehyde should be strongly considered at least through investigations occurring three days after the fire and personal formaldehyde air monitoring is recommended during investigations.

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DISCLOSURE

There are no conflicts of interest regarding this work. The findings and conclusions are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Keywords

aldehydes; combustion products; contaminants; fire investigators; occupational exposure; particulate

INTRODUCTION

The fire service has witnessed growing evidence of increased occupational cancer risks (Daniels et al. 2014, 2015; Glass et al. 2014; IARC. 2010; Jalilian et al. 2019; Lee et al.,2020; LeMasters et al. 2006; Pukkala et al. 2009; Tsai et al. 2015) and a growing body of literature focused on job-related exposures that may be encountered (Englesman et al, 2020; Gill & Britz-McKibbin 2020). At the same time, sudden cardiac events are a leading cause of on-duty deaths in the fire service and the documented increased risk post-suppression (Smith et al. 2019) may be partially attributed to fireground exposures (Baxter et al. 2010; Smith, Barr & Kales, 2013; Smith et al. 2016). It has been well documented that today's structure fires can produce high levels of airborne particulate and numerous known, probable and possible carcinogens such as aldehydes, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) (Austin et al. 2001a, 2001b; Jankovic et al. 1991). While much of this occupational exposure research has focused on training fires (Fent et al. 2019; Fernando et al. 2016; Kirk and Logan. 2015; Stec et al. 2018; Wingfors et a. 2018) or structural fire responses (Baxter et al. 2014; Bolstad-Johnson et al. 2000; Fent et al. 2013,2018; Hoppe-Jones et al. 2021; Keir et al 2017 & 2020; Poutasse et al. 2020), potential risks for post-fire scene investigators have not been characterized nearly as well.

Fire investigators typically expect to encounter lower levels of airborne environmental contamination than structural firefighters because their activities take place after fire extinguishment. Occupational exposure risks during fire responses are often characterized as a high magnitude but for a relatively short duration. Heavy insulating firefighter personal protective equipment (PPE) and self-contained breathing apparatus (SCBA) are well suited for these risks. The timeframe for active fire investigation can range from immediate post suppression to several days or longer after fire suppression has been completed. Oftentimes, due in part to a lack of perceived risk from an active fire along with important challenges in completing documentation tasks, the use of PPE among fire investigators is limited, potentially increasing their susceptibility to carcinogenic exposures. The International Association of Arson Investigators (IAAI) Fire Investigator Health and Safety Best Practices guidelines recommends fire investigators monitor for carbon monoxide and hydrogen cyanide during the incident (International Association of Arson Investigators, 2020). However, many other known and possible carcinogens are likely to remain present during overhaul activities (activities conducted to look for hidden and/or smoldering fires) and during the fire investigation period (Weiss & Miller 2011; Gainey et al. 2018).

Typical fire investigation activities may be conducted over an extended time period and include a wide range of activities. Investigators are commonly called on to document a fire scene through collecting pictures, creating diagrams, and identifying patterns. In some cases, investigators will have to shovel debris, remove materials, and collect samples from

the burned area. Investigators may work with canine agents to ascertain potential use of accelerants or other occupations in order to determine the origin and cause of the fire. The IAAI has defined categories of fire scenes for investigation based on time after fire extinguishment has been completed (International Association of Arson Investigators, 2020).

- HOT SCENE A: Fire has been extinguished and overhaul is in progress or has not yet commenced.
- HOT SCENE B: Fire was fully extinguished/overhauled for less than two hours.
- WARM SCENE: Fire was fully extinguished at least two hours ago but for less than 72 hours.
- COLD SCENE: Fire has been fully extinguished for more than 72 hours and not generating detectable or visible products of combustion.

Few studies have focused on the time periods specific to fire investigators. Kinnes and Hine (1998) conducted environmental monitoring during investigations at timeframes ranging from Hot Scene A to Warm Scene and found formaldehyde concentrations up to 0.18 ppm along with total and respirable dust at time-weighted average concentrations up to 5.3 and 1.3 mg/m^3. It was noted that several fire investigators, who did not wear respiratory protection, experienced both eye and respiratory irritation during these investigations. Sjostrom et al (2019) assessed environmental exposure encountered by nine police forensic investigators (PFIs) during investigations and found they were exposed to benzene, naphthalene, and total dust during Warm and/or Cold Scene investigations. In 2013, Fent et al reported PAH and particulate concentrations during overhaul (similar exposure profile to Hot Scene A) were higher than background concentrations, and particulate and certain VOC concentrations during investigation (Hot Scene B) were higher than background levels in some experiments.

Several studies have reported on the environmental conditions during post-suppression overhaul process. Bolstad-Johnson et al (2000) conducted an air monitoring study during the overhaul phase of 25 structure fires and found that concentrations of acrolein (1 fire), carbon monoxide (5 fires), glutaraldehyde (5 fires) and formaldehyde (22 fires) exceeded applicable American Conference of Governmental Industrial Hygienists (ACGIH) or National Institute for Occupational Safety & Health (NIOSH) ceiling values, while benzene exceeded NIOSH short-term exposure limits (STEL) at two fires. Importantly, the 10-minute average CO concentrations did not predict concentrations of other products of combustion. Weiss and Miller (2011) measured airborne concentrations of several chemicals during the overhaul phase. They also found CO levels did not predict other chemicals' presence or concentrations at fire scenes. After 1 hour, most products were no longer detectable with their instrumentation. Finally, Fent et al (2018) characterized airborne concentrations of combustion byproducts produced during the overhaul phase of 12 controlled residential fires in single family structures and found that total PAHs and benzene exceeded ACGIH excursion limit for coal tar pitch volatiles and NIOSH STEL, respectively. While these studies have not focused specifically on the fire investigators' activities and exposures, they provide an important guidance for Hot Scene A environments to which initial fire investigators may operate.

Fire investigators are currently lacking comprehensive data upon which to determine appropriate levels of PPE that should be worn from Hot A through Cold Scene investigations and what monitoring should take place to support these decisions. The objective of this study is to characterize airborne contaminants that may be encountered while investigating a residential fire scene from within a few minutes after fire extinguishment to up to 5 days post fire suppression.

METHODS

Study Design

The study design and sampling strategy during these investigation activities is outlined in Figure 1. This project was conducted alongside a subset (N=18) of experiments designed to study firefighting tactics. Two identical structures were constructed for this study, with nine experiments conducted with fires ignited in a bedroom in one building, and nine separate experiments involved furnishings in a common room (open floor-plan kitchen and living room) in the second building. A minimum of three days was provided between each bedroom and common room experiment to allow the buildings to be rehabilitated by clean up and construction crews (damaged furnishings, finishes and structure removed, replace and repainted) and for replacement of instrumentations. During four experiments (Bedroom Experiments #3 and #6, Common Room Experiments #3 and #6), building rehabilitation was delayed for 5 days to allow investigation activities to occur during Warm (1- and 3-days post fire) and Cold (5-days post fire) scenes. For these four experiments, fire scenes were preserved by closing up the structure with OSB sheeting screwed to the outside of compromised door and window frames (a standard practice for situations where investigation by additional parties is necessary). Sheeting from the front door was subsequently removed during these additional 60-minute investigation periods.

Prior to each fire, baseline pre-fire area air samples were collected over 60 minutes in the room where the fire was ignited. Post-fire investigation phase area air samples were collected after all fire was suppressed to characterize conditions during Hot Scene A timeframes (N=8), Hot Scene B timeframes (N=18), as well as Warm and Cold Scene timeframes (N=4). No fire investigation activities were conducted during Hot Scene A, but firefighters did conduct overhaul as necessary. Hot Scene B investigations were initiated within an hour of initial suppression, but after overhaul had been completed. During the Hot Scene B and Warm Scene timeframes, typical fire scene investigation activities were conducted for 60 minutes. During the Cold Scene investigation timeframe, investigators again began with typical documentation activities, then portions of drywall ceilings and walls were removed to inspect fire effects on structural components and building systems.

Test structure, fuel load and fire ignition

Two identical, wood framed 150 m^2 single-story, four-bedroom, two-bathroom residential structures were used in this study (Figure 2). Fiberglass batt insulation was installed in the ceiling and exterior wall stud cavities under OSB sheathing. All interior walls and ceilings were lined with 16mm gypsum board and finished with two coats of latex paint.

At least 24 hours prior to each experiment, the structure was freshly painted and fully furnished in each of the four bedrooms, two bathrooms, kitchen and living room to represent fuel load conditions typical of a 21st century residential structure in the United States. The kitchen fires included electrical wiring, connection boxes, and plastic drainpipe that would be exposed inside of the cabinets. In addition, items commonly found in kitchen, ranging from a coffee maker to a full recycling bin, were included as they were composed of a variety of plastics found in a residential setting. The furnishings were all purchased in new condition and where possible, the base materials used in their construction were determined and documented. Fuel arrangements in the bedroom and common room (open floor plan kitchen and living room) are shown in Figure 3. Details of materials for all furnishings and contents are included in Supplemental Materials for the kitchen (Table S1), living room (Table S2) and bedroom (Table S3). There were no additional contents such as clothing in closets and drawers of the bedroom or magazine and personal electronics throughout the structure.

Bedroom fires were ignited with an electric match located in the corner of the upholstered chair where the seat cushion met the armrest nearest the mattress. Living room fires were also ignited with an electric match located in the corner of the upholstered sofa furthest from the front door. The kitchen ignition was initiated from an approximate 4 kW propane burner upon which a 19 cm diameter aluminum cooking tray with 180 ml (3/4 cup) canola oil was placed on stand 13 cm above the burner. After the oil reached its auto-ignition temperature, the burner was shut down, and the flame produced by the oil spread to adjacent materials on the counter and kitchen cabinets and, depending on timing of firefighting activities, on to the living room furnishings.

Firefighting and fire investigation activities

A team of interior and exterior firefighters coordinated firefighting suppression, ventilation and search activities using a variety of tactics and timing of actions In experiments where water was applied quickly and/or ventilation was limited, the fire's thermal damage was fairly localized near the area of origin. On the other hand, multiple experiments in both bedroom and common room fires transitioned to flashover, resulting in flames extending from each opening of the fire compartment and subsequent extensive floor-to-ceiling, wall-to-wall damage.

After the initial attack team determined that fires were fully suppressed, a second firefighting team entered the structure to monitor conditions and were instructed to conduct minimal overhaul to preserve the fire scenes for investigation. Overhaul was complete once it was determined that all visible flaming had been confirmed to be suppressed and the oxygen and carbon monoxide levels had returned to baseline.

Area air Sampling

Table 1 provides a summary of the area air sample collection including sampling media, flow rates ranges and analysis methods utilized to characterize aldehydes, fiber, hydrogen cyanide (HCN), hydrogen sulfide (H2S), mercury, metals, PAHs, and VOCs as well as direct read instruments to quantify particulate and asphyxiant gases. The VOC method was

used to quantify benzene, ethyl benzene, toluene, xylenes and styrene (BTEXS) as well as naphthalene (which, based on previous publication is expected to be the PAH in the highest abundance) and total VOCs.

Pre- and post-fire exposure sampling always occurred in the compartment where the fire originated as shown in Figure 2. Sampling media and pump intakes were located roughly 5 feet from the floor to approximate breathing zone height. Thomas MegaLite or SKC QuickTake-30 (SKC, Eighty Four, PA) sample pumps with media were run for 60 minutes to collect samples for Pre-Fire, Hot Scene B, Warm Scene and Cold Scene timeframes. Gilian BDX-II sampling pump (Senisdyne, St Petersburg, FL) ran for an average of 35 minutes (range 30 to 41 minutes) during Hot Scene A. All sampling pumps were calibrated pre and post sampling events (+/− 5%) and all sampling media were stored in either a refrigerator and/or freezer as appropriate prior to sampling and prior to shipment (on ice) to the analytical laboratory.

Direct read data was collected for carbon monoxide, hydrogen cyanide and hydrogen sulfide using a Multi-RAE Pro Model # PGM-6248 or Model # PGM-6228 (RAE Systems by Honeywell, San Jose, CA). Aerosol measurements for PM1, PM2.5, respirable, PM10 and total PM size fractions were collected using a DustTrak DRX Model #8534 (TSI Incorporated, Shoreview, MN).

Detection rates for H2S, HCN, fiber and metal samples collected during the first 12 experiments were low or zero, thus sampling was terminated and data will not be reported here.

Data Analysis

Descriptive statistics (i.e. median, range, percentage of samples with concentrations above the limit of detection (LOD)) and statistical analyses were carried out using SPSS (v 27, IBM, Armonk, NY). LOD divided by square root of two was assigned to non-detectable concentrations (Hornung & Reed. 1990).. Wilcoxon Signed-Ranks Test were used to compare differences in area air concentrations among paired timeframes (pre-fire vs. Hot Scene B in all 18 experiments, pre-fire vs Hot Scene A in the subset of 8 experiments). Further analysis using an independent samples Mann-Whitney U test were completed to test whether area air concentrations varied by fire location (bedroom vs common room). Significance was set at an alpha of 0.05. Because the direct-reading particle instrument took measurements every second, summary statistics for concentrations of each particle dimension were conducted on the arithmetic means and peak values during baseline and Hot Scene B.

RESULTS

Particulate Results

Hot Scene B—Average and peak particulate concentrations measured pre-fire and during Hot Scene B for a range of cut-off dimensions are presented in Tables 2 and 3, respectively. During the pre-fire sampling period, particulate levels were relatively low, with respirable particle concentrations, below 25 μg/m^3 on average, although transient peak values

averaged 134 μg/m^3. However, during Hot Scene B activities, particulate concentration increased significantly for all particle sizes ($p<0.05$ *for all sizes*) with average respirable concentrations increasing to approximately 115 μg/m^3 and peak values averaging nearly an order of magnitude higher. Average pre-fire particulate concentrations were commonly higher in the bedroom than in the common room ($p<0.05$ *for all sizes*), possibly due to the bedroom being smaller and less air flow. Conversely, Hot Scene B particulate were generally higher in common room compared to bedroom, though statistically significant increases ($p<0.05$) were limited to PM1, respirable and PM2.5 concentrations. Observations noted that peak particulate values appeared when fire debris on horizontal surfaces were disturbed as drywall or pieces of kitchen cabinets fell or were removed. Increases were also noted during simulated investigation activities that included shoveling and moving furnishings.

Warm & Cold Scene Particulates—In most cases, the 60-minute average and peak respirable and total particulate concentrations during the 1-day and 3-day post-fire investigation timeframe (Warm Scene) were similar in magnitude to Hot Scene B measurement though some variation occurred depending on investigation activities (Figure 4). The 5-day post experiment (Cold Scene) deviated significantly across all particle sizes as drywall ceiling and wall were removed. Particulate concentrations increased dramatically during Cold Scene activities with peak values of respirable particulate well above 10,000 μg/m^3 and in one case exceeding 40,000 μg/m^3. Total particulate levels increased more so, possibly due to the difference in the size of particulate produced by the gypsum board and fiberglass insulation compared to products of combustion. Bedroom Experiment #3, Bedroom Experiment #6 and Common Room Experiment #3 followed similar trends, but the Common Room Experiment #6 was unique among this group. Of the four experiments studied in these extended time periods, this fire generated more damage to the room which resulted in some drywall falling from the ceiling prior to the Hot Scene B investigation and some additional drywall fell from the ceiling during the 3-day post-fire investigation.

Vapor Phase Results

While a wide range of vapors were detected during the study, this paper will focus on BTEXS compounds, naphthalene, total VOCs, (Table 4) and aldehydes (Table 5). Of the 12 aldehydes targeted by the DNPH/HPLC method, only compounds that were detected in more than 50% of all samples are included in Table 5.

Hot Scene A & B Vapors—While BTEXS compounds were identified in many of the pre-fire samples, concentrations of all compounds increased in Hot Scene A (*all* $p<0.05$), and benzene ($p<0.001$), ethyl benzene ($p=0.003$), and styrene ($p=0.001$) remained significantly elevated above pre-fire levels in the 60-minute Hot Scene B sample. Average Hot Scene A concentrations of benzene were below the most conservative exposure limit (NIOSH recommended exposure limit (REL) of 320 μg/m^3 (0.1 ppm. Naphthalene concentrations increased significantly during Hot Scene A ($p=0.012$) but returned to levels similar to pre-fire concentrations during Hot Scene B sampling. Total VOCs also dramatically increased during Hot Scene A ($p=0.012$) but returned to values lower than pre-fire on average during the Hot Scene B time period ($p=0.010$). Much of the high pre-fire total VOC concentrations can be attributed to components of adhesives, solvents

and paint (e.g., Propanoic acid, 2-methyl-, 3-hydroxy-2,2,4-trimethylpentyl ester and 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate) as well as freshly installed carpeting, curtains and kitchen cabinetry/countertops that may have been off-gassing.

Several aldehydes were detected in the pre-fire samples, but concentrations of all aldehydes other than hexanal and pentanal increased significantly ($p<0.05$) during Hot Scene A measurements. By Hot Scene B, formaldehyde had largely returned to pre-fire levels, while acetaldehyde ($p<0.001$), benzaldehyde ($p=0.004$), and propanal ($p=0.005$) remained significantly elevated above pre-fire levels. In all eight of the experiments where Hot Scene A measurements were collected, concentrations of formaldehyde were above the NIOSH Ceiling limit of 123 μg/m^3 (0.1 ppm). None of the Hot Scene B concentrations exceeded this ceiling limit, though 17 were above the most conservative NIOSH work-shift REL of 20 μg/m^3 (0.016 ppm). Also of note, 13 of the pre-fire measurements exceeded this REL, and the largest pre-fire concentrations were found in the common room, possibly due to the off-gassing of newly installed cabinetry and countertop in these rooms. While Hot Scene A concentrations of acetaldehyde were measured up to 3,360 μg/m^3, none of the acetaldehyde concentrations exceeded the ACGIH ceiling limit of 45,000 μg/m^3 (25 ppm).

Warm & Cold Scene Vapors—Benzene concentrations during the 1-day, 3-day and 5-day post-fire investigation timeframes tend to decay from the relatively low levels in Hot Scene B to near non-detectable levels by the Cold Scene measurement period at the end of the experiment (Figure 5). The Warm and Cold Scene trends for naphthalene concentrations were less consistent at 1-day post fire but declined to below 10 μg/m^3 by 5-days post-fire. The more heavily damaged Common Room Experiment #6 again displayed unique characteristics, particularly at 3-days post fire when additional ceiling material fell into the room being investigated.

Acetaldehyde and formaldehyde concentrations during the 1-day post-fire investigation period were increased from the Hot Scene B measurements in three of the four experiments, prior to decaying to near pre-fire levels by the end of the experiment at 5-days post fire (Figure 6). In Bedroom Experiment #3 and Bedroom Experiment #6, formaldehyde concentrations exceeded the NIOSH ceiling limit at 1-day post-fire and the NIOSH work-shift REL at 3-days post fire. Concentrations were typically lower in the common room experiments, possibly due to the proximity of the open door in that compartment which was used for egress. Common Room Experiment #6 again displayed unique characteristics, with an initial decrease in concentrations of both acetaldehyde and formaldehyde at 1-day post fire, but a subsequent increase after the partial ceiling collapse during the 3-day post fire investigation period.

DISCUSSION

The most important findings of this study are that 1) elevated and hazardous levels of airborne particulate may be encountered during all phases of the post-fire scene investigation depending on the activities of the fire investigator and 2) airborne formaldehyde concentrations could exceed recommended exposure limits in extended phases of the post-fire investigation. This study provides the first controlled investigation experiment

that allows fire scene investigation phases to be characterized from immediately after fire suppression through investigations that may occur up to 5-days after the fire. The fire damage that resulted from these experiments ranged from isolated damage with an obvious point of origin to full compartment involvement in fire even with identical fuel packages. This range of post-fire damage was considered to be typical based on authors' experience who were also fire investigators GH, DM.

Particle concentrations throughout investigation

Exposure to fireground particulate has important health implications related to risks for both occupational cancer and sudden cardiac events, which are two of the primary health concerns in today's fire service. Median PM2.5 levels encountered during Hot Scene B were 103.5 μg/m^3 for all experiments and 191 μg/m^3 for the subset of common room fires, which correspond to air quality index (AQI) values of 176 (Unhealthy) and 241 (Very Unhealthy) (AirNow.gov, 2021). The lowest average PM2.5 concentration over the 60-minute Hot Scene B timeframe was 16 μg/m^3 (59 AQI – Moderate) while the highest was 498 μg/m^3 (498 AQI – Hazardous). Note, AQI indices are based on 24-hour average outdoor concentrations and are intended for the general public, while these measurements are averaged over one hour. Still, the general public is encouraged to minimize their time outdoors (to lower their exposure time) when the AQI is at or exceeds the "Very Unhealthy" level.

The total particulate concentrations measured in this study (mean 211 μg/m^3, median 127 μg/m^3, range 19–823 μg/m^3) are comparable to the nine total dust measurements reported by Sjostrom et al (2019) (mean 176 μg/m^3, range 70–314 μg/m^3). Likewise, Kinnes and Hine (1998) measured respirable dust concentrations ranging from undetectable (<100 μg/m^3) to 360 μg/m^3 while the total dust concentrations ranged from 200 to 1,100 μg/m^3 from four residential fire scenes (although one additional office fire where data was collected during time periods that appeared to be similar to Hot Scene A resulted in concentrations of 1,200 μg/m^3 and 5,300 μg/m^3, respectively). Finally, Fent et al (2013) reported widely varying PM10 concentrations during two largely identical simulated fire investigations (80 μg/m^3 and 700 μg/m^3). The current study compliments these small existing studies with a larger data set that includes a more detailed partitioning of particle dimensions. Additionally, the time resolved nature of these measurements allowed for the evaluation of transient events that led to increased particle levels, including handling drywall, furniture movement, and active shoveling.

By extending particulate data collection to several days after the immediate post-fire investigation period, important changes in concentration were determined. Peak concentrations from transient events were generally not as high as the immediate post-fire operations other than Common Room Experiment #6 when some additional ceiling collapsed. Importantly, at the 5-day post-fire investigation period, investigators actively removed drywall from the compartment ceilings and walls in order to inspect structural components and building systems that may have been compromised by the fire. During these days, the median respirable and total particulate levels over the 60-minute investigation period were 826 μg/m^3 and 1,841 μg/m^3 with peak levels of 20,950 μg/m^3 and 47,050 μg/m^3.

Particulate in the respirable size range are capable of penetrating and depositing into the gas exchange regions of the respiratory system (Donaldson, Li & MacNee, 1998). While the exact composition of this particulate was not determined in this study, it would likely be composed of large hydrocarbon molecules and a variety of adsorbed toxicants. Epidemiologic studies have consistently shown strong associations between elevations in ambient fine particulate concentrations and increases in hospital admissions and mortality rates in the general population (Dockery et al. 1993; Pope & Dockery, 2006; Seaton et al, 1995). In the fire service, exposure to particulate hazards has been proposed as an important contributing factor for sudden cardiac events (Baxter et al. 2010; Smith, Barr & Kales, 2013; Smith et al. 2016).

These results highlight the need for particulate respiratory protection during all phases of the fire investigation process, particularly when drywall is being removed or handled. In the fire service, terminology related to a ‘cold scene’ or ‘cold zone’ typically refer to a hazard-free condition, which may not be appropriate considering the particulate risks encountered during these fire investigation activities. Furthermore, while this study has focused on post-fire investigations, this information may also be useful to inform post-fire reconstruction occupations who are likely to be pulling down smoke- and fire-damaged drywall as they rehab the buildings.

Vapor concentrations throughout investigation

Many of the existing fireground exposure studies in the literature focus on PAH and VOC contamination, specifically naphthalene and benzene. For the investigation timeframes reported in this study, the concentrations of VOCs are low relative to exposure limits, particularly for Hot Scene B, Warm and Cold Scenes. The magnitude of benzene and naphthalene in Hot Scene B timeframe are slightly higher than concentrations found in the fire investigations reported by Sjostrom et al (2019) – 30.6 vs 19.3 $\mu g/m^3$ and 9.9 vs 4.6 $\mu g/m^3$ – but in both studies, concentrations were well below applicable exposure limits. Kinnes and Hine (1998) reported similar naphthalene concentrations as our study (30 and 36 $\mu g/m^3$) in the two residential fire scenes they studied. In two staged experiments where investigation occurred more rapidly after fire suppression, naphthalene increased to 99 and 200 $\mu g/m^3$, which is within the range of Hot Scene A concentrations measured here.

The Hot Scene A measurements are best compared to studies evaluating overhaul exposures. During overhaul of a residential fire structure, Fent et al (2018) reported benzene concentrations of approximately ~210 $\mu g/m^3$ (0.065 ppm), which is slightly higher than 139±79 $\mu g/m^3$ measured in Hot Scene A here. The overhaul period in Fent et al (2018) lasted 11–19 minutes compared to the 30–41 minute Hot Scene A period here which likely allowed more time for smoke dissipation. Bolstad-Johnson et al (2000) measured benzene in 53 of the 95 samples collected during overhaul, but average values among the detectable samples was 1,230±1,365 $\mu g/m^3$ (0.383±0.425 ppm). During overhaul, Fent et al (2018) did not report any benzene concentrations over STEL, while Bolstad-Johnson et al (2000) reported 2 of 25 fires exceeded STEL. In this study, benzene samples found in Hot Scene A were not above the STEL. Bolstad-Johnson et al (2000) measured naphthalene at similar concentrations to what was reported in Hot Scene A. Overall, the concentration

of the PAH and VOC compounds most commonly reported during overhaul activities are similar to those measured during Hot Scene A. This study shows a relatively consistent decline in concentrations from Hot Scene A to Hot Scene B, then in Warm and Cold Scene investigation periods. In all cases, the concentrations remained below applicable exposure limits.

However, aldehyde results present a different picture, with formaldehyde concentrations detected above the most protective work-shift REL and even exceeding the NIOSH Ceiling limit in multiple timeframes and experiments. During overhaul, Bolstad-Johnson et al (2000) reported detectable levels of formaldehyde in 86 of 96 samples collected with average concentrations of 307±309 μg/m^3 (0.25±0.252 ppm) and maximum concentrations reaching 1,450 μg/m^3 (1.18 ppm). The average sample concentration exceeded the NIOSH Ceiling limit and was similar, though slightly lower than our Hot Scene A concentrations (420.5±25.6 μg/m^3). Additionally, Bolstad-Johnson et al (2000) reported detectable levels of acetaldehyde in 71 of 96 samples collected with average concentrations of 615±740 μg/m^3 (0.34±0.41 ppm) and maximum concentrations reaching 3,160 μg/m^3 (1.75 ppm). Acetaldehyde had the highest detection rate and overall concentration levels and again was lower than our results (1389±940 μg/m^3).

While the concentration of all aldehyde compounds dramatically declined from Hot Scene A to Hot Scene B, the formaldehyde levels remained above the NIOSH work-shift REL for a majority of thee experiments. Furthermore, concentrations of formaldehyde were found to have increased beyond the Hot Scene B levels during subsequent investigation periods at 1-day and 3-days post-fire for several experiments. For both Bedroom Experiments #3 and #6, these values exceeded the NIOSH Ceiling limit at 1-day post. In three of these four experiments, detectable levels of formaldehyde remained at 5-days post-fire.

Current guidance for practicing fire investigators recommends the use of "*Multi-gas area monitoring, including VOCs, PAHs, oxygen enrichment/deficiency, carbon monoxide, and hydrogen sulfide*" (International Association of Arson Investigators, 2020). Based on the results of this study, the authors would suggest that investigators also regularly monitor for formaldehyde in addition to the other compounds on this list to determine appropriate control measures such as respiratory protection. Many 4-gas and 6-gas monitors carried in the fire service do not contain sensors for this compound. Previous studies have shown that typical fire service monitoring for compounds such as carbon monoxide, oxygen or hydrogen sulfide is not adequate to warn of the presence of other compounds such as formaldehyde. Additionally, these findings reinforce the need to consistently wear respiratory protection throughout the post-fire scene investigation. SCBA provides the highest level of respiratory protection from aldehydes, particulate and other unknown airborne hazards, however, use of SCBA isn't always feasible during investigations due to logistics of maintain air supply over long duration activities. The feasibility of using alternative respiratory protection measures such as powered air purifying respirators or full-face respirators with a CBRN cartridge should be studied for their application in this occupation. The results of this study support adding to the IAAI guidance the importance of vapor protection from formaldehyde at least through the Warm Scene investigation period.

Limitations

While this study greatly expands the available data for estimating risk during post-fire scene investigation, there are important limitations to consider. The number of samples collected remains relatively small, particularly with datasets focused on Warm and Cold Scenes. And while the data presented in this study are more tightly grouped than samples collected from field studies such as Bolstad-Johnson et al (2000) and Sjostrom et al (2019), important variability remains. Additionally, fire investigation activities were similar during these measurement periods other than Hot Scene A, but the actions taken did vary based on timing and amount of scene disturbance deemed necessary by the investigators during their observations. Finally, it is likely that varying levels of airborne contaminants would have been measured with different fuel packages and if other contaminants such as flame retardants or per- and polyfluoroalkyl substances (PFAS) were specifically targeted.

Future Work

Future studies could expand on this area air sampling study by collecting data from personal air concentrations during specific investigation activities. It is also recommended that future studies characterize the presence of other contaminants of interest including asbestos fibers (or surrogates) isocyanates, flame retardants and PFAS and the potential for all of these compounds to cross-contaminate tools, vehicles and fire stations. Additionally, efforts to quantify chemical absorption during an investigation through biomonitoring, could identify relative risk of exposure through dermal absorption or inhalation routes. These studies can improve fire investigators design and use of PPE. Finally, this work suggests the importance of studying exposure for post-fire reconstruction workers and insurance adjustors as well as canines used as accelerant detection animals during investigations.

CONCLUSIONS

This study provides the first series of controlled investigation experiments that allows fire scene investigation phases to be related to previously reported overhaul concentrations and extended out to 5-days after the fire. Elevated and hazardous levels of airborne particulate may be encountered during all phases of the post-fire scene investigation and depends on the activities of the fire investigator as much as the time since the fire. High levels of particulate across the size ranges measured here were noted when drywall was removed from the structure, highlighting the need to protect fire investigators' airway from particulates any time this activity is conducted. Airborne concentrations of aldehydes were often higher than VOCs. While airborne concentrations of benzene and naphthalene are often reported in highest concentrations during live fire response and training, formaldehyde and acetaldehyde concentrations appeared to be the most predominant compounds (relative to their exposure limits) in Hot Scene A through Cold Scene investigation timeframes. In fact, it was found that formaldehyde concentration could exceed recommended exposure limits in several phases of the investigation, including ceiling limits during Hot Scene A and the 1-day post fire Warm Scene investigation session. This finding reinforces the importance of including vapor protection from formaldehyde at least through the Warm Scene investigation while also possibly carrying monitors to detect formaldehyde during investigations and potentially post-fire reconstruction activities. Furthermore, findings of

high levels of particulate throughout all phases of investigation highlights the importance of post-investigation decontamination of PPE (on scene preliminary exposure reduce measures and advanced cleaning) and skin (including on-scene clean up and/or wipes as well as showering as quickly as possible).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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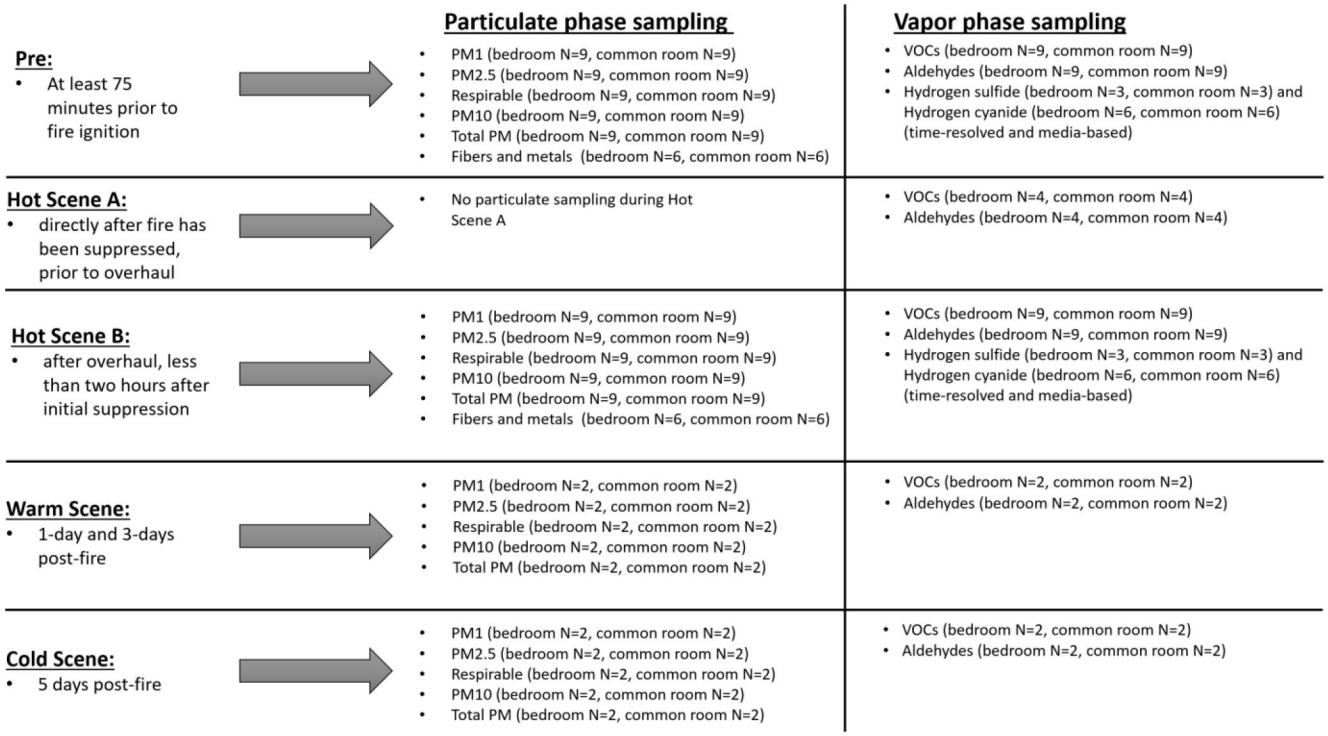

Figure 1.
Study design and sample collection strategy.

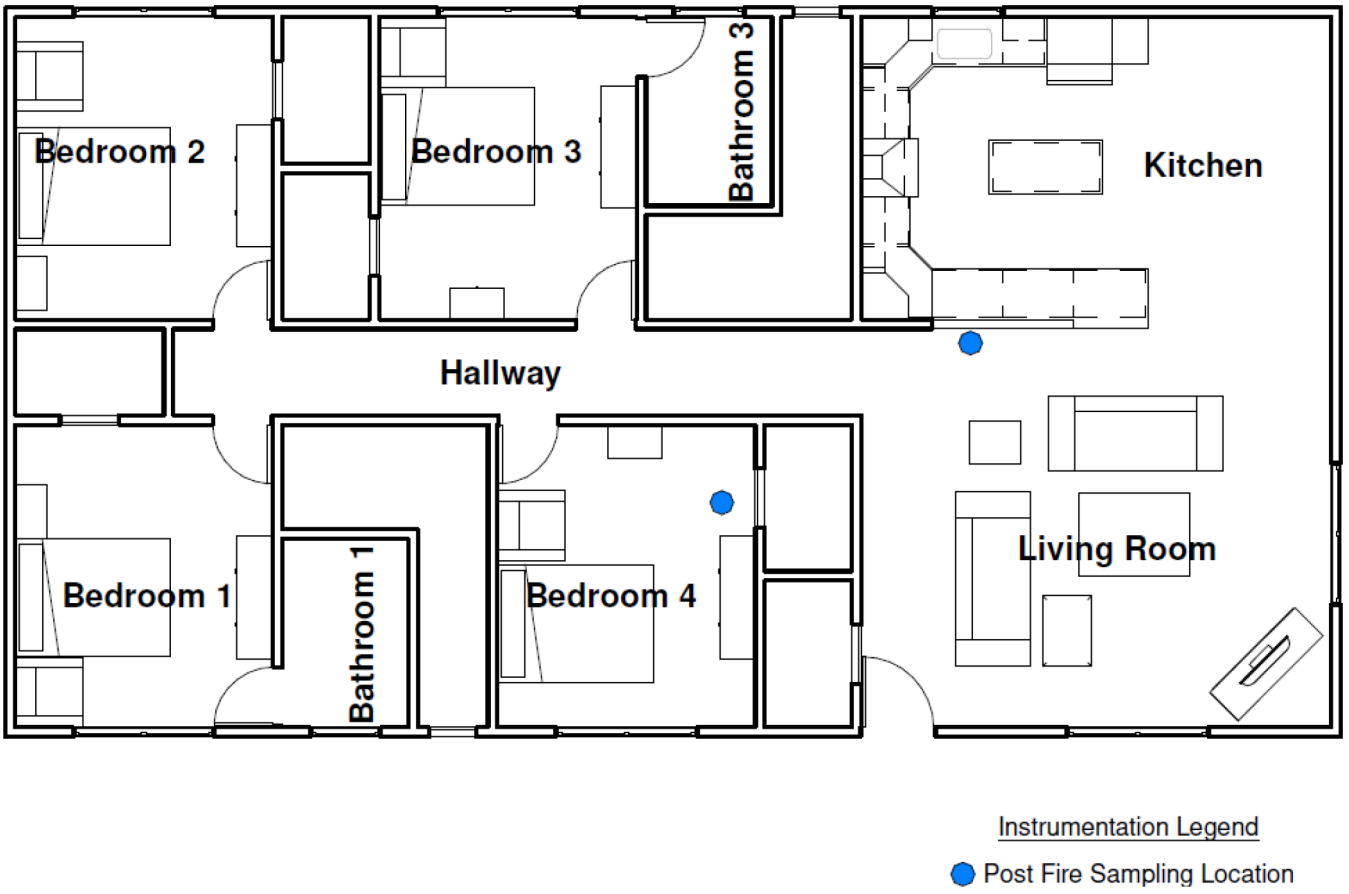

Figure 2.
Structure layout and sampling locations selected for the bedroom and common room (kitchen and living room) fire experiments.

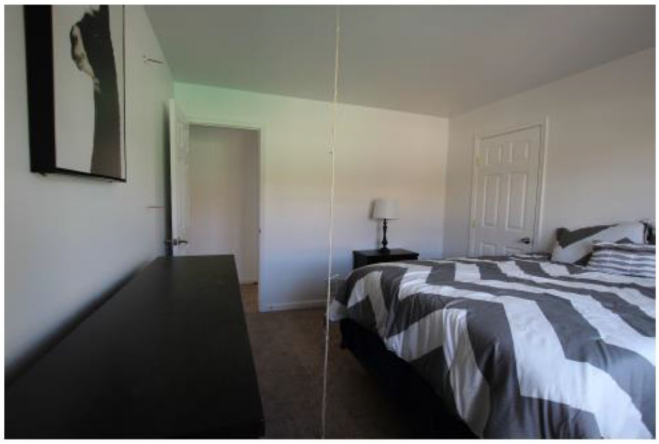



Figure 3.
Photographs of typical furnishings in the bedroom fires (top) and common room fires including kitchen (middle) and living room (bottom).

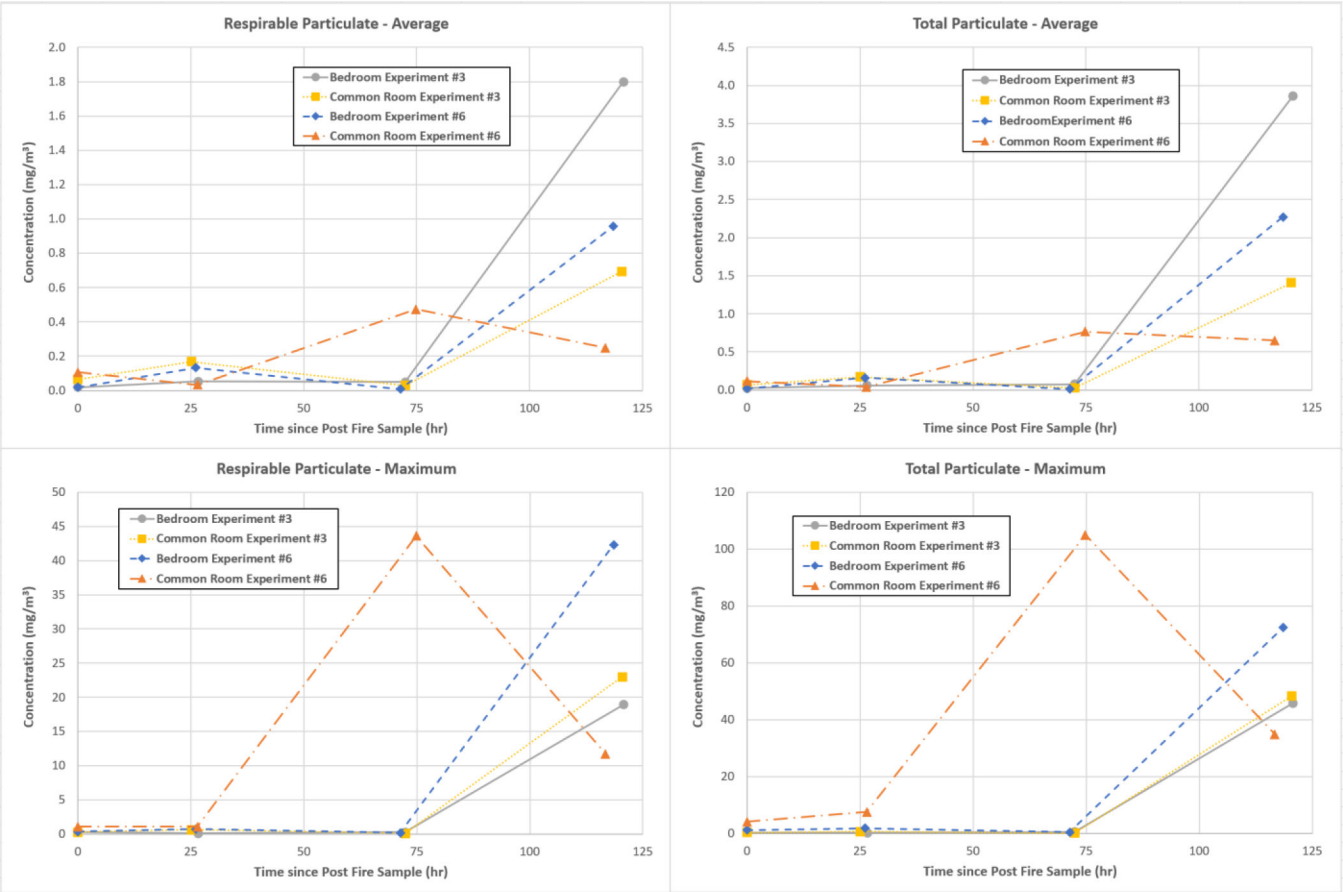

Figure 4.

Respirable (left) and total (right) 60-minute average (top) and peak (bottom) particulate concentrations (μg/m^3) for four experiments including Hot Scene B (immediately post-fire sample at time = 0 hour), Warm Scene (1-day and 3-day post fire samples at approximately 24 and 72 hours) and Cold Scene (5-day post fire samples at approximately 120 hours).

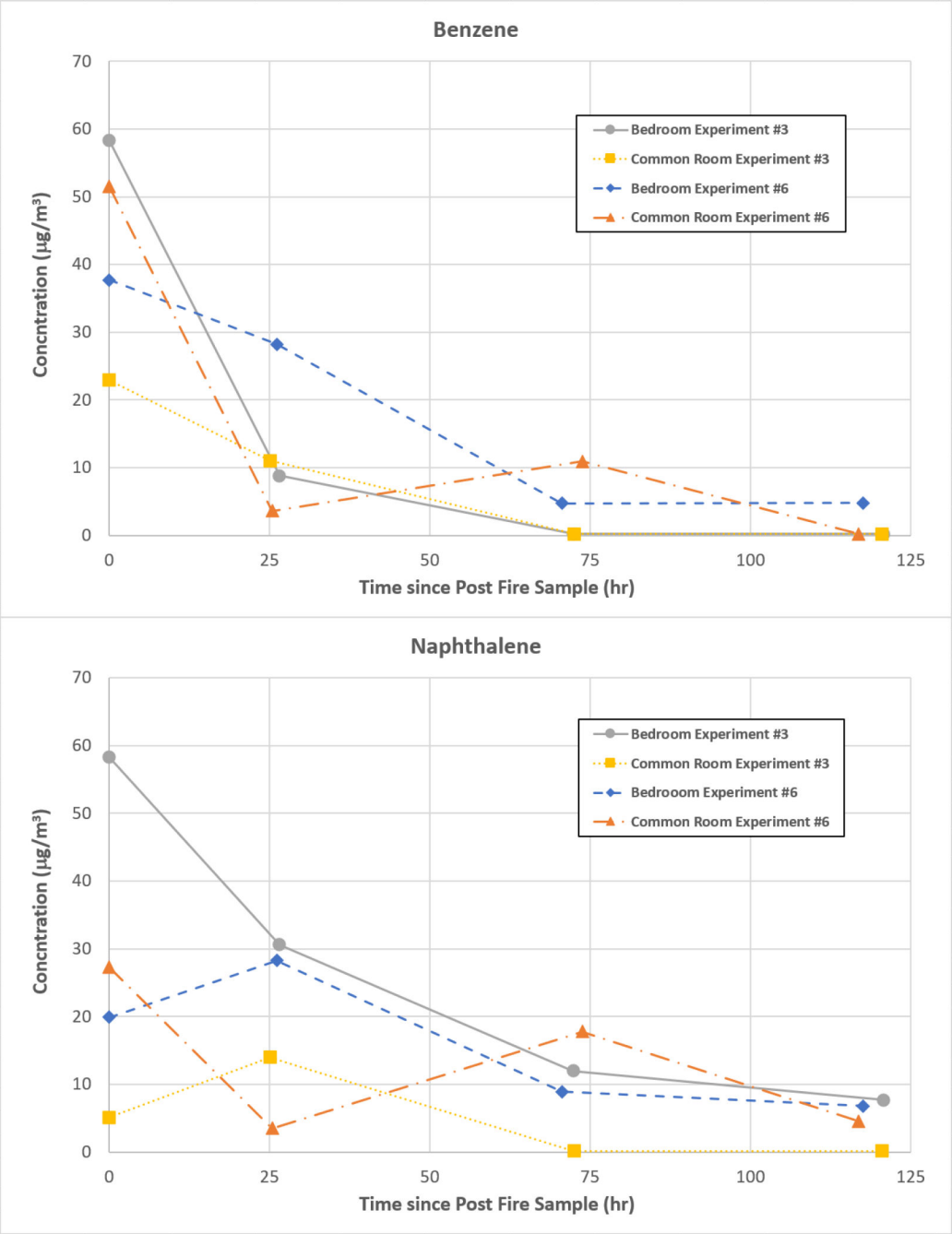

Figure 5.

Benzene (top) and naphthalene (bottom) 60-minute time-weighted average concentrations (µg/m^3) for four experiments including Hot Scene B (immediately post-fire sample at time = 0 hour), Warm Scene (1-day and 3-day post fire samples at approximately 24 and 72 hours) and Cold Scene (5-day post fire samples at approximately 120 hours).

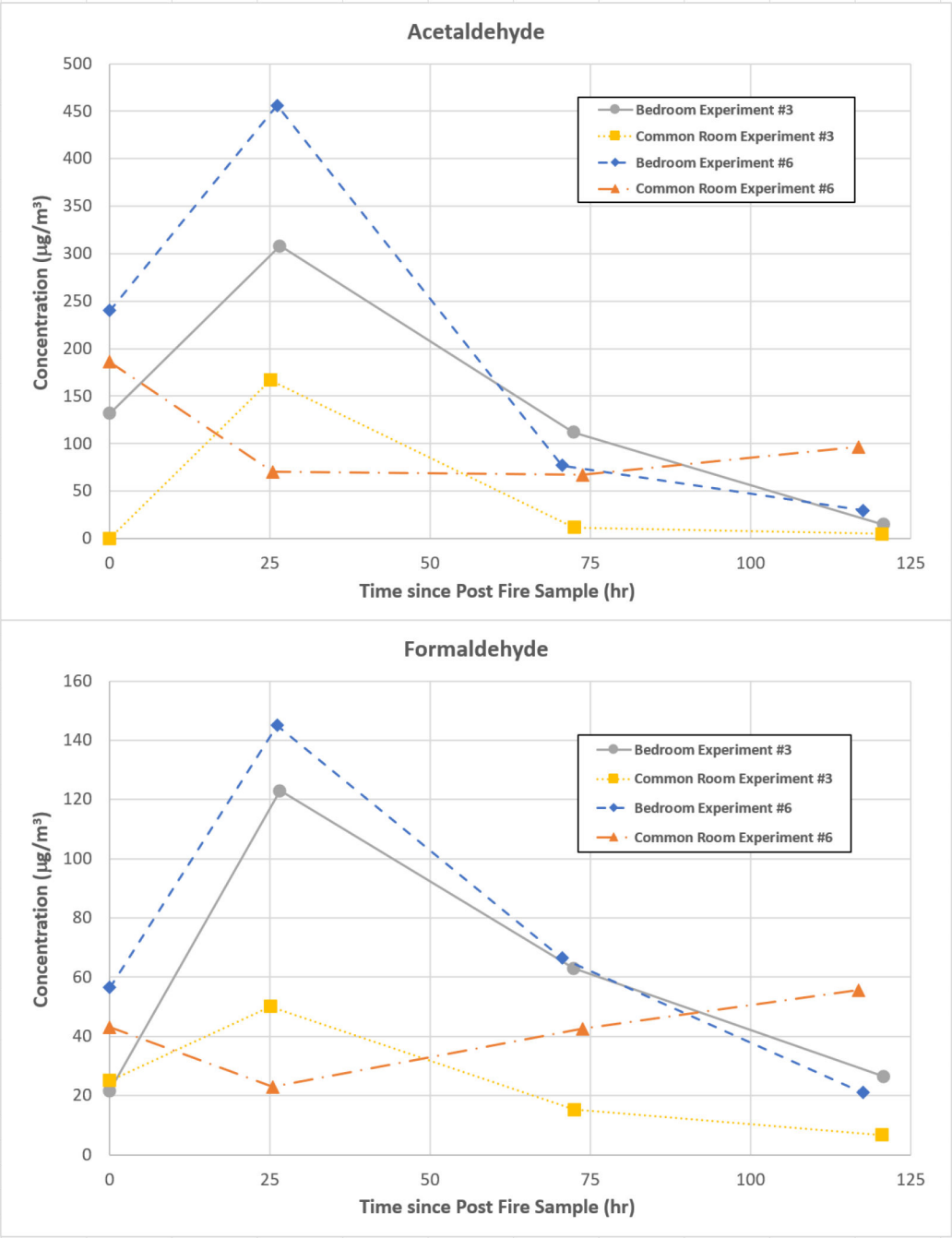

Figure 6.

Acetaldehyde (top) and formaldehyde (bottom) 60-minute time-weighted average concentrations (µg/m^3) for four experiments including Hot Scene B (immediately post-fire sample at time = 0 hour), Warm Scene (1-day and 3-day post fire samples at approximately 24 and 72 hours) and Cold Scene (5-day post fire samples at approximately 120 hours).

Table 1.

Area air sampling collection and analysis methods

Compound	Sampling media	Flow rate (L/min) [A]	Analytical method
Aldehydes	Supelco LpDNPH S-10 cartridge	0.7–0.96	ASTM D5197
Fibers	Zefon 25mm cassette 0.8μm MCE	1.5–13.5 [B]	NIOSH 7400
Hydrogen Cyanide	Soda lime tube	0.15–0.53	NIOSH 6017
Hydrogen Sulfide	Charcoal tube	0.2	NIOSH 6013M
Mercury	Anasorb C300 tube	0.16–0.25	NIOSH 6009
Metals	Zefon 37mm 0.8μm MCE	1.5–3.3	NIOSH 7300M
Volatile Organic Compounds	Charcoal tube	0.25–0.60	EPA TO-17; ASTM 6196
Particulate	DustTrak DRX – 1 sample/sec (PM1, PM2.5, Respirable, PM10, Total)		
Asphyxiant gases	MultiRAE Lite – 1 sample/sec (HCN, H2S, Carbon Monoxide (CO))		

[A] Flow rates were increased for sampling during the shorter Hot Scene A measurement

[B] Flow rates for fiber sampling were reduced after initial samples were overloaded with soot in an attempt to collect viable measurements.

Table 2.

Average particulate concentration (μg/m^3) for submicron (PM1), less than 2.5μm (PM2.5), respirable, less than 10μm (PM10), and total fractions for all eighteen experiments as well as bedroom and common room fire experiments over a 60 minute data collection period. Data are presented as median (range).

	Total (N=18)					
			Bedroom (N=9)		*Common Room (N=9)*	
	Pre	***Hot Scene B***	***Pre***	***Hot Scene B***	***Pre***	***Hot Scene B***
PM1^{B,C}	20 (1–91)	96.5 ^{A} (15–490)	29 (13–91)	27 (15–311)	14 (1–29)	186 ^{A} (63–490)
PM2.5^{B,C}	21 (1–98)	103.5 ^{A} (16–498)	32 (14–98)	28 (16–317)	15 (1–29)	191 ^{A} (64–498)
Respirable^{B,C}	**24.5 (1–117)**	**114.5**^{A}**(17–509)**	**40 (17–117)**	**30 (17–322)**	**19 (1–29)**	**196**^{A}**(66–509)**
PM10^{B}	32.5 (1–202)	121 ^{A} (18–556)	67 (24–202)	35 (18–423)	25 (1–44)	208 ^{A} (68–556)
Total^{+}	36 (1–292)	127 ^{A} (19–823)	82 (25–292)	40 (19–823)	27 (1–85)	221 ^{A} (69–596)

^{A} p<0.05 relative to pre-fire concentrations

^{B} p<0.05 pre-fire concentrations in bedroom are different from common room

^{C} p<0.05 Hot Scene B concentrations in bedroom are different from common room

Table 3.

Peak particulate concentration (μg/m^3) for submicron (PM1), less than 2.5μm (PM2.5), respirable, less than 10μm (PM10), and total fractions for all eighteen experiments as well as bedroom and common room fire experiments. Data are presented as median (range).

	Total (N=18)		***Bedroom (N=9)***		***Common Room (N=9)***	
	Pre	***Hot Scene B***	***Pre***	***Hot Scene B***	***Pre***	***Hot Scene B***
PM1	118 (6–295)	1,045 ^{A} (197–23,500)	117 (61–236)	459 ^{A} (197–11,300)	119 (6–295)	1,290 ^{A} (275–23,500)
PM2.5	119.5 (6–301)	1,090 ^{A} (200–23,700)	119 (62–244)	474 ^{A} (200–11,500)	120 (6–301)	1,300 ^{A} (279–23,700)
Respirable	**134 (8–314)**	**1,180^A(205–23,800)**	**152 (65–292)**	**497^A(205–12,000)**	**122 (8–314)**	**1,310^A(280–23,800)**
PM10	212.5 (12–516)	1,385 ^{A} (279–23,800)	238 (70–516)	675 ^{A} (279–16,000)	167 (12–418)	1,660 ^{A} (287–23,800)
Total	281.5 (37–981)	1,625 ^{A} (393–34,700)	418 (89–981)	1,170 ^{A} (429–34,700)	270 (37–775)	1,990 ^{A} (393–23,800)

^{A}p<0.05 relative to pre-fire concentrations

Table 4.

Airborne concentration of VOCs (μg/m^3) as 60-minute time weighted averages for pre-fire and Hot Scene B and averaged over 30–41 minutes in Hot Scene A. Data are presented as median (range).

		Pre N=18	Hot Scene A N=8	Hot Scene B N=18
Benzene	Median (Range)	**1.2 (ND-15.9)**	**121 (34.8–302)** ^{A}	**30.6 (2.9–89.4)** ^{A}
	% Detect	*50%*	*100%*	*100%*
Toluene	Median (Range)	6.6 (ND-117)	56.6 (19.4–113)^A	8.8 (ND-29.8)
	% Detect	*89%*	*100%*	*83%*
Ethyl Benzene	Median (Range)	ND (ND-4.5)	26.4 (ND-66.4)^A	3.7 (ND-12.0)^A
	% Detect	*22%*	*63%*	*61%*
Xylene	Median (Range)	2.5 (ND-60.7)	48.5 (19.5–350)^A	2.7 (ND-33.5)
	% Detect	*56%*	*100%*	*61%*
Styrene	Median (Range)	3.5 (ND-18.8)	82.3 (ND-204)^A	35.2 (ND-76.3)^A
	% Detect	*78%*	*88%*	*83%*
Naphthalene	Median (Range)	**10.5 (ND-73.7)**	**118 (64.0–213)** ^{A}	**9.9 (ND-58.3)**
	% Detect	*78%*	*100%*	*94%*
Total VOCs	Median (Range)	616 (35–1,770)	3,830(1,460–10,700)^A	199 (14–1,360)^A
	% Detect	*100%*	*100%*	*100%*

ND indicates below quantifiable level (< 2 μg/m^3)

^{A}p<0.05 relative to pre-fire concentrations

Table 5.

Airborne concentration of aldehydes (μg/m^3) as 60-minute time weighted averages for pre-fire and Hot Scene B and averaged over 30–41 minutes in Hot Scene A. Data are presented as median (range).

		Pre N=18	Hot Scene A N=8	Hot Scene B N=18
Acetaldehyde	Median (Range)	**16.5 (7.5–75.6)**	**1,380 (205–3,360)** ^{A}	**171 (ND-416)**^{A}
	% Detect	***100%***	***100%***	***94%***
Benzaldehyde	Median (Range)	5.0 (1.8–17.0)	69.0 (25.6–176)^A	9.0 (5.0–16.4)^A
	% Detect	*100%*	*100%*	*100%*
Formaldehyde	Median (Range)	**30.0 (14.8–167.0)**	**356 (140–775)**^{A}	**36.1 (16.5–82.5)**
	% Detect	***100%***	***100%***	***100%***
Hexanal	Median (Range)	43.8 (8.7–104)	49.8 (14.7–122)	11.5 (2.4–28.6) ^{A}
	% Detect	*100%*	*100%*	*100%*
Pentanal	Median (Range)	15.1 (3.6–50.8)	20.8 (ND-56.7)	5.7 (ND-13.3) ^{A}
	% Detect	*100%*	*75%*	*67%*
Propanal	Median (Range)	8.4 (ND-95.0)	318 (ND-1,070)^A	36.3 (6.0–94.0)^A
	% Detect	*83%*	*88%*	*100%*

2-dimethyl benzaldehyde, 2,5-dimethyl benzaldehyde, 3- and/or 4-dimethyl benzaldehyde, butanal, 3-methyl butanal and 2-butenal were detected in less than 50% of all samples.

ND indicates below quantifiable level (< 2 μg/m^3)

^{A}p<0.05 relative to pre-fire concentrations