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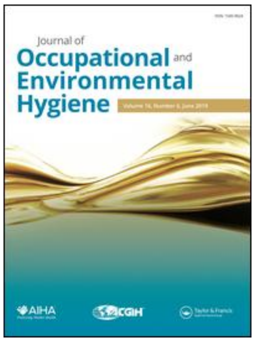

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Understanding airborne contaminants produced by different fuel packages during training fires

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ABSTRACT

Fire training may expose firefighters and instructors to hazardous airborne chemicals that vary by the training fuel. We conducted area and personal air sampling during three instructional scenarios per day involving the burning of two types (designated as alpha and bravo) of oriented strand board (OSB), pallet and straw, or the use of simulated smoke, over a period of 5 days. Twenty-four firefighters and ten instructors participated. Firefighters participated in each scenario once (separated by about 48 hr) and instructors supervised three training exercise per scenarios (completed in 1 day). Personal air samples were analyzed for polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and hydrogen cyanide during live-fire scenarios (excluding simulated smoke). Area air samples were analyzed for acid gases, aldehydes, isocyanates, and VOCs for all scenarios. For the live-fire scenarios, median personal air concentrations of benzene and PAHs exceeded applicable short-term exposure limits and were higher among firefighters than instructors. When comparing results by type of fuel, personal air concentrations of benzene and PAHs were higher for bravo OSB compared to other fuels. Median area air concentrations of aldehydes and isocyanates were also highest during the bravo OSB scenario, while pallet and straw produced the highest median concentrations of certain VOCs and acid gases. These results suggest usage of self-contained breathing apparatus (SCBA) by both instructors and firefighters is essential during training fires to reduce potential inhalation exposure. Efforts should be taken to clean skin and clothing as soon as possible after live-fire training to limit dermal absorption as well.

KEYWORDS
Firefighters; HCN; isocyanates; PAHs; particulate; VOCs

Introduction

Firefighters are occupationally exposed to a number of airborne pollutants and contaminants during emergency fire responses, including polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), polychlorinated biphenyls (PCBs), dioxins, plasticizers, flame retardants, hydrogen cyanide (HCN), hydrogen chloride, and other respirable particulates.[1,2] Some of these compounds may also be produced during live-fire training, and may contribute substantially to firefighters' exposure over their career, depending in part on the relative amount of time spent in training vs. emergency responses. Occupational exposure during training may also depend on the fuel package used in training, as the pyrolysis of OSB is different than the pyrolysis of pallet and straw.

A meta-analysis conducted in 2006 indicated that firefighters have increased risk of testicular, multiple myeloma, non-Hodgkins lymphoma, and prostate cancer.[3] Following this meta-analysis, Daniels et al.[4] conducted a retrospective study of 30,000 firefighters and found increased mortality and incidence risk for

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cancers of the esophagus, intestine, lung, kidney, and oral cavity, as well as mesothelioma. Daniels et al.[4] also found a dose-response relationship between fire-runs and leukemia and fire hours and lung cancer.[5] While a number of risk factors increase cancer risks, firefighters' inhalation exposure to toxic combustion products like PAHs and benzene are thought to play an important role.

Many fire departments require live-fire training for their members in order to maintain competency and certifications. Often, firefighters and officers serve as instructors. Training fires may account for a large portion of firefighters and instructors' total occupational exposure to airborne contaminants, particularly for instructors who may see three to five live fires per day over a period of several weeks or even months. These exposures may increase their risk of cancer, cardiovascular disease, and other chronic diseases. A recent study of fire instructors in Australia found a dose-response relationship between estimated training exposures and cancer incidence.[6]

Fuels used for fire training varies, but often follows recommendations from National Fire Protection Association (NFPA) 1403 *Standard on Live Fire Training Evolutions* in an attempt to control the risk involved with live fires.[7] Such training scenarios will often utilize fuels like pallets and straw, which tend to produce light grey smoke for obscuring visibility. Some training institutes will also use engineered wood products such as oriented strand board (OSB) in addition to pallet and straw to produce fire conditions that more closely replicate residential structure fires (e.g., darker smoke and higher temperatures).[8] Other fire training programs have begun using simulation technologies like theatrical smoke or pepper fog to produce training environments, removing the live-fire scenarios altogether. While some dangerous airborne contaminants like PAHs and VOCs are expected to be low during simulated smoke exercises, chemical hazards like insoluble aerosols and formaldehyde have been measured at concentrations above or just below occupational exposure limits during these exercises.[9]

A number of studies have investigated firefighters' exposures during various types of live-fire training exercises, including those that used firewood, particle chipboard, plywood, and heating oil as fuel sources.[10–12] These studies generally show that firefighters can be exposed to high airborne concentrations of aromatic hydrocarbons (e.g., benzene) and PAHs during training fires. However, the potential exposure from airborne toxicants during repeated training fires has not been fully characterized, and is of particular interest for instructors who may encounter several repeated exposures over a given year.

The primary goal of this study was to gain a better understanding of the concentrations of airborne contaminants (i.e., PAHs, VOCs, acid gases, isocyanates, aldehydes, and HCN) produced during training scenarios. Over a period of several days, firefighters and instructors conducted training scenarios involving pallet and straw, OSB, and simulated smoke. Personal air samples were collected from firefighters and instructors during scenarios involving two different types of OSB and pallet and straw. Area air measurements were collected inside the structure during active fire, as well as downwind from the fire and in the background before the fire was started for all scenarios.

This study design allowed us to investigate the hazardous airborne substances instructors and firefighters are exposed to during routine training scenarios with broad applicability in the U.S. fire service. By following the same methodology, we were also able to compare airborne contaminants from this study involving training fuels with our previous study where we examined controlled residential fires containing modern furnishings.[13]

Methods

Study population

This study was performed at the University of Illinois Fire Service Institute (IFSI), with collaboration from the National Institute for Occupational Safety and Health (NIOSH) and Underwriters Laboratories (UL) Firefighter Safety Research Institute (FSRI), and was approved by Institutional Review Boards at NIOSH and the University of Illinois. Individuals with any known cardiovascular disease, gastrointestinal complications, who were pregnant, used tobacco, or were younger than 18 or older than 55 years of age were excluded from the study. All firefighters were required to have completed a medical evaluation consistent with NFPA 1582 and a self-contained breathing apparatus (SCBA) fit-test in the past 12 months. All firefighters were also required to wear their SCBA prior to entering the structure. Twenty-four firefighters (22 male, 2 female) from nine states across the United States participated in this study. Ten fire instructors (9 male, 1 female) also participated.

Study design

The study design is described in detail elsewhere.[14] Briefly, two sets of five instructors (designated Alpha and Bravo) worked alternating days (3 study days in 5 calendar days each). The study used a repeated measures design in which firefighters participated in training scenarios involving three different fuel packages and enclosures commonly used to simulate single-family residential fires. Three crews of four firefighters and five instructors were assigned to Alpha Group (Days 1, 3, and 5) and three additional crews of four firefighters and five instructors were assigned to Bravo Group (Days 2, 4, and 6). On each study day, each crew participated in one training scenario and the instructors supervised three training scenarios. The training scenarios took about 10 min to complete with 3 hr between each scenario. Each firefighter had approximately 48 hr between training scenarios and each instructor had about 40 hr between his/her last scenario of the day and the next scenario.

For all three training scenarios, the firefighters had the same objective—to suppress a two-room fire and rescue two simulated occupants of the structure. The three scenarios differed primarily by fuel package and type or orientation of the structure is described as follows.

- **Pallet and straw scenario**—Fires were ignited using three pine wooden pallets and one bale of straw in two separate bedrooms in a single-story concrete training structure. All pallets used in the study were new and had not been used for shipping or handling any materials that could potentially contaminate the wood. The structure was laid out similar to a mid-20th century single family dwelling (Supplemental Materials, Figure S1).
- **OSB scenario**—Fires ignited in burners using two pallets and one bale of straw along with OSB in each of two separate bedrooms in a T-shaped metal shipping container-based prop (Supplemental Materials, Figure S2). Two different types of OSB were used, identified in the paper as alpha OSB (used for the alpha groups) and bravo OSB (used for the bravo groups). Each type of OSB contained the same Engineered Wood Association APA rating for 7/16” thickness (panel grade 24/16, exposure 1). One-and-a-half sheet of the 7/16” alpha OSB were placed along the ceiling to provide adequate fuel supply for the training fires. Because of supply limitations, we only had access to 1/4” sheets of the Bravo OSB sheathing. One sheet of this OSB was cut in half and stacked together and then two sheets were also stacked together and placed along the ceiling. This effectively produced one-and-a-half sheets of Bravo OSB with a similar thickness and orientation to the alpha OSB fuel package. According to their safety data sheets (SDS), both OSB sheathing contained phenol formaldehyde adhesive and polymeric methylene bisphenyl diisocyanate (pMDI) adhesive, but the exact volume percentage of each is unknown. The primary difference between the SDSs for the two types of OSB was that Bravo OSB reported <0.01% of free formaldehyde, while alpha OSB reported <0.1% of free formaldehyde.
- **Simulated smoke scenario**—An electronic means of simulating a fire that also incorporated glycol-based simulated smoke generation (Attack Digital Fire System, Bullex; Albany, NY) was utilized in a building constructed from metal shipping containers to have an identical layout to a mid-20th century single family dwelling (Supplemental Materials, Figure S1)

The order in which the training fire scenarios were introduced was staggered. Alpha firefighters and instructors started with the simulated smoke scenario, then pallet and straw, and ended with the OSB scenario. Bravo firefighters and instructors began with the OSB scenario, followed by pallet and straw, and then simulated smoke.

Each crew was composed of two firefighters assigned to fire attack, who advanced the fire hose from an engine and suppressed all active fires, and two firefighters assigned to search and rescue, who performed forcible entry and then searched for and rescued two simulated trapped occupants (75 kg manikins). During each scenario, two instructors were assigned as stokers or fire starters (ignited the fuel packages and controlled ventilation for fire and smoke development) and three instructors were assigned as company officers (two supervised the attack team and one supervised the search and rescue team). Both the firefighters and instructors were required to wear a full complement of NFPA compliant personal protective equipment (PPE), including SCBA while inside the structures during the training scenarios. Instructors assigned as stokers donned their SCBA masks prior to ignition, while instructors assigned as company officers and the firefighters generally donned their SCBA masks just before entry. Some firefighters went “on-air” as soon as they exited the fire truck/engine (upon arrival at the scene), while others went “on-air” just

Table 1. Summary of area air sampling methods.

Sampling performed[A]	Scenario[B]	n	Duration of scenario (min)	Sampling time during scenario (min)[C]	Method
Acid gases: hydrogen bromide, hydrogen fluoride, hydrogen chloride, phosphoric acid	Pallet and straw	6	26–30	23–30	Silica gel tube (Supelco ORBO 53), 500 mL/min, analyzed by ion chromatography (NIOSH method 7903)
	Alpha OSB	3	25–28	12–26	
	Bravo OSB	3	25–31	7–33	
Aldehydes: acetaldehyde, acrolein, formaldehyde	Pallet and straw	6	26–30	24–31	XAD-2 tube (SKC 226-117), 200 mL/min, analyzed by GC/NPD (OSHA method 52)
	Alpha OSB	3	25–28	16–29	
	Bravo OSB	3	25–31	15–41	
	Simulated smoke	6	22–31	20–32	
Isocyanates: methyl isocyanate, methylene diphenyl diisocyanate (MDI), phenyl isocyanate	Alpha OSB	3	25–28	9–25	Asset denuder sampler (Supleco EZ4), 200 mL/min, analyzed by LC/MS/MS (ISO method 17734)
	Bravo OSB	3	25–31	12–45	
VOCs: 64 compounds	Pallet and straw	4	26–30	∼15	6 L evacuated canister with 15-min regulator and fritted pre-filter, analyzed by GC/MS (EPA method TO-15)
	Downwind	4		∼15	
	Alpha OSB	2	25–28	∼15	
	Downwind	2		∼15	
	Bravo OSB	2	25–31	∼15	
	Downwind	2		∼15	
	Simulated smoke	4	22–31	∼15	
Respirable particles (downwind only)	Pallet and straw	6	26–30	22–28	Aluminum cyclone (SKC 225-01-02), tared PVC, 2.5 L/min, analyzed gravimetrically, 50% cut-point of 4 µm
	Alpha OSB	2	25–28	25–29	
	Bravo OSB	3	25–31	21–25	

GC/NPD = gas chromatography/nitrogen phosphorous detector; LC/MS/MS = liquid chromatography/tandem mass spectrometry; GC/MS = gas chromatography/mass spectrometry; VOCs = volatile organic compounds; MDI = methylene diphenyl diisocyanate.
[A]Area air samples were also collected for PAHs, BTEX, and HCN during the simulated smoke exercises by placing samplers inside the training structure using the same methodology as for personal air sampling (n = 6 for each analyte).
[B]OSB scenarios also included two pallets and one bale of straw. Pallet and straw scenarios included three pallets and one bale of straw.
[C]Occasionally, sampling time was less than the duration of the scenario because of pump faults due to extreme conditions. Sampling times higher than the scenario duration were due to a delay in turning off the sampling pumps.

prior to entering the structure. Individuals chose when to don SCBA based on their own FD policies around SCBA use. The buildings' windows and doors were opened during or shortly after fire suppression efforts to ventilate the structures as is common in coordinated firefighter training scenarios (simulating best practice on the fire ground).

After each scenario, the firefighters and instructors doffed their turnout gear in an empty gear and materials storage bay ∼60–70 m west of the burn structures, which in most cases was upwind from the prevailing wind direction, and then promptly entered an adjacent climate-controlled transport container for additional sample and specimen collections that are reported in a companion paper.[15]

Personal air sampling

Personal air samples were collected for PAHs, HCN, and benzene, toluene, ethyl benzene, and xylenes (BTEX) using NIOSH methods 5528, 6010, and 1501, respectively.[16] The sampling pumps were stored in pockets or straps on the outer shell of the turnout jackets, and sampling media were positioned near the collar of the jackets. Flow rates were set at 1 L/min for the PAH samplers and 200 mL/min for the HCN and BTEX samplers. At least two firefighters and three instructors were sampled during the live-fire scenarios (i.e., alpha OSB, bravo OSB, and pallet and straw). Personal air samples were not collected during simulated smoke scenarios because concentrations were expected to be low. Instead, area air samples for PAHs, HCN, and VOCs were collected inside the simulated smoke structure. Median sampling times for each analyte ranged from 9–12 min for firefighters and 25–30 min for instructors (Supplemental Materials, Table S1).

Area air sampling

Table 1 provides a summary of the area air sampling methods for each of the training scenarios. Tygon tubing (Saint-Gobain, Malvern, PA) was wrapped in insulation and inserted into the pallet and straw and OSB structures (Figures S1 and S2) at a height of ∼0.9 m to approximate crouching or crawling height. Areas were chosen that would be most representative of the location where firefighters were working during a large portion of the response. The tubing was attached to the inlet of the sampling media on the outside of the structures with outlet of the media being connected to sampling pumps. Use of tubing to collect air from the structure was done to protect the sampling media from hot gases. After each scenario, the tubing was rinsed with soap and water and dried with compressed air, visually removing loose particulate. However, no testing was done to determine the efficiency of cleaning. New Tygon tubing was used for each training day. For the simulated smoke scenarios—where thermal hazards did not exist—sampling trains were positioned inside the training structure also with media at ∼0.9 m height. For all scenarios, the sampling pumps were started with ignition (or start of smoke generation) and stopped as soon as possible after completion of the scenario (once instructors left the scene). Afterward, sampling media were capped and stored in a -20 °C freezer prior to shipment to the laboratory.

In addition to the substrate-based sampling, we also performed whole-gas sampling to measure VOCs. Prior to sampling, a 15-min regulator was attached to an evacuated canister (6 L stainless steel). The regulator contained a 2 m piece of copper tubing with a fritted pre-filter at the end. For live-fire scenarios, this tubing was wrapped in insulation and inserted into the structures at a height of ∼0.9 m, while the canisters remained outside the structures. For the simulated smoke scenarios, the canisters and tubing were placed inside the structure (with the sample inlet at ∼0.9 m height). Once the fire was ignited (or smoke machine started), the regulator was opened to permit air to be collected over a ∼15 min period. After this duration, the remaining pressure was recorded and the regulator was closed.

VOC samples and respirable particles were also collected downwind of the training scenarios to provide an estimate of airborne exposure potential for support personnel not directly involved in the firefighting activities. The downwind samples were ∼7 m from the structures (similar to distance of incident command) and at a height of 1 m. Their downwind position was contingent on the prevailing wind direction (according to windsock) and placed in locations without nearby obstructions. No other weather conditions were monitored. In addition, VOC and respirable particle samples were collected inside the training structures before igniting fires to estimate background levels.

Data analysis

Descriptive statistics and other data analyses were carried out using SAS software (version 9.4, SAS Institute, Cary, NC). Pump faults due to overloading of sampling media with particulate were common for the area air samples (VOCs, respirable particles, aldehydes, isocyanates, and acid gases) collected during the fire period and for the personal air samples (PAHs, HCN, and BTEX). The time the pumps ran from ignition (area air) or arrival at the structure (personal air) until the end of the scenario (or when the pumps faulted) was used to calculate the volume of air collected in determining the time-weighted averaged air concentrations. Personal air samples that did not run for at least 3 min of the response were excluded because they may not accurately represent the average concentrations during the response. Three min was chosen as the cut-off because it took approximately 2 min for the firefighters to force open the prop and enter the structure, and thus would only include approximately 1 min of operation inside the structure where concentrations are expected to be the highest. In total, five PAHs, five HCN, and five BTEX personal air samples were excluded due to a sampling time of less than three min.

Total PAHs were calculated by summing the 15 quantified PAHs. Zero was used for non-detectable concentrations in this summation. Minimum detectable concentrations were calculated for non-detectable measurements by dividing the limits of detection by the volume of air collected. A Kruskal-Wallis test was used to test whether personal air concentrations varied by type of participant (instructor vs. firefighter). Further analyses using the Kruskal–Wallis test were completed to compare differences in personal air concentrations among pallet and straw, Alpha OSB, and Bravo OSB scenarios, as well as differences in area air concentrations among these different scenarios. Supplementary box-plots were created with lower quartile, median, and upper quartile indicated with the box and whiskers extending to the minimum and maximum of the distribution.

Results

Personal air concentrations for HCN, total PAHs, and VOCs

Table 2 provides a summary of the personal air concentrations grouped by type of participant (instructor vs. firefighter) and fuel package (pallet and straw, Alpha OSB, Bravo OSB) for HCN, total PAHs, and benzene. OSB scenarios (Alpha and Bravo) included two pallets and one bale of straw, while the pallet and straw scenarios consisted of three pallets and one bale of straw. As is typical of live-fire training, the entire fuel package was not consumed on any of the

Table 2. Summary of personal air concentrations by type of participant and fuel package.

Analytes	Type of participant	Type of Fuel Package/Job Assignment[B]	N	ND (%)	Median	Range	P-value firefighter vs. instructor	P-value alpha OSB vs. bravo OSB
HCN (ppm)	Instructor	Pallet and straw	28	0	0.608	0.0913–2.31	<0.01	0.57
	Firefighter		19	0	2.240	0.691–6.96		
	Instructor	Alpha OSB	12	0	0.376	0.154–1.760	0.06	
	Firefighter		9	0	0.830	0.137–2.02		
	Instructor	Bravo OSB	11	0	0.457	0.270–0.882	0.02	
	Firefighter		6	0	0.889	0.645–1.29		
Residential Fire Study HCN (ppm)[A]	N/A	Attack	13	0	33.5	4.10–100	N/A	N/A
	N/A	Search	17	29	0.085	<0.060–106	N/A	
Total PAHs (mg/m^3)	Instructor	Pallet and straw	17	0	2.78	1.23–6.89	0.02	
	Firefighter		9	0	3.39	2.27–18.10		
	Instructor	Alpha OSB	9	0	4.44	1.77– 9.21	0.07	<0.01
	Firefighter		5	0	8.33	4.95–29.9		
	Instructor	Bravo OSB	9	0	14.2	3.21–19.9	<0.01	
	Firefighter		6	0	34.0	22.2–56.4		
Residential Fire Study total PAHs (mg/m^3)[A]	N/A	Attack	19	0	23.8	7.46–78.2	N/A	N/A
	N/A	Search	16	0	17.8	9.77–43.8	N/A	
Benzene (ppm)	Instructor	Pallet and straw	28	0	3.00	1.09–7.10	<0.01	
	Firefighter		20	0	4.18	2.33–11.9		
	Instructor	Alpha OSB	12	0	4.01	0.470–12.1	0.02	<0.01
	Firefighter		11	0	7.30	2.93–25.6		
	Instructor	Bravo OSB	12	0	9.09	5.25–26.2	<0.01	
	Firefighter		10	0	31.7	18.1–54.9		
Residential Fire Study benzene (ppm)[A]	N/A	Attack	17	0	40.3	12.4–322	N/A	N/A
	N/A	Search	22	0	37.9	12.0–306		

[A]Results from Fent et al.[13] were provided for comparison.
[B]We stratified by fuel package in the current study and job assignment in the previous study. OSB scenarios also included two pallets and one bale of straw. Pallet and straw scenarios included three pallets and one bale of straw.
[C]Most protective short-term occupational exposure limit for: HCN NIOSH STEL (4.700 ppm), Total PAHs ACGIH excursion limit for coal-tar pitch volatiles (1 mg/m^3), and Benzene NIOSH STEL (1.000 ppm).

scenarios, so slight differences in pre-fire fuel package weights are not expected to influence fire behavior. Note that firefighters and instructors wore SCBA while inside the structure during the trainings and were protected from inhaling these substances such that these values represent potential exposures available to those operating in these conditions, not necessarily the direct exposures. Nearly all personal air HCN concentrations were below the NIOSH STEL (4.70 ppm),[17] regardless of type of participant or fuel package. In contrast, median concentrations of benzene exceeded the STEL (1.00 ppm)[17] for both instructors and firefighters for all three fuel packages used in the live-fire scenarios. Similarly, total PAH levels exceeded the ACGIH® excursion limit for coal-tar pitch volatiles (1.00 mg/m^3)[18] for both instructors and firefighters for all three live-fire scenarios. Of the 15 PAHs analyzed in this study, naphthalene was responsible for 66–68% of the total PAH concentration depending on the fuel package (Supplemental materials, Table S2).

Personal air sampling during combustion of Bravo OSB measured higher concentrations of total PAHs and benzene compared to Alpha OSB. Median personal air concentrations of total PAHs and benzene were lower for pallet and straw compared to both types of OSB. Interestingly, firefighters training in a fire with pallet and straw as the fuel package had the highest median HCN air concentrations (although still below the NIOSH STEL).

After stratifying by type of participant, firefighters generally had higher personal air concentrations than instructors for HCN, total PAHs, and benzene. Benzene concentrations were higher for firefighters compared to instructors for all fuel packages. Total PAH concentrations for firefighters were higher than for instructors in the Bravo OSB scenarios.

Supplementary figures are provided that compare styrene, ethylbenzene and toluene (Figures S3–S5) concentrations by fuel package and type of firefighter. Results were similar to PAHs and benzene as firefighters responding to the Bravo OSB scenarios had the highest levels, but all concentrations were below each compounds' respective STEL. Area air samples of PAHs, HCN, and benzene taken during simulated smoke scenarios (instead of personal air samples) were low or near the minimum detectable concentration (< 0.0021 mg/m^3).

Area air concentrations for acid gases, aldehydes, isocyanates, and VOCs

Table 3 provides a summary of area air concentrations of acid gases inside the structure by fuel package. All acid gas concentrations were below the minimum detectable concentrations (<0.175 mg/m^3) for the simulated smoke scenarios. Hydrogen bromide and phosphoric acid concentrations were below the minimum detectable concentrations for all scenarios (< 0.826 and <0.551 mg/m^3, respectively). Hydrogen chloride and hydrogen fluoride concentrations were highest during pallet and straw scenarios compared to alpha OSB and bravo OSB, with median concentrations above the ACGIH ceiling limit (2.00 mg/m^3).[18] The hydrogen chloride and hydrogen fluoride air concentrations were similar between the Alpha OSB and Bravo OSB scenarios.

Table 4 summarizes the area air concentrations of aldehydes and isocyanates inside the structure by type of training scenario, along with the most conservative applicable exposure limits. Almost all aldehyde air concentrations measured during simulated smoke

Table 3. Area air concentrations of acid gases inside structure by type of fuel package.

Acid gases[A]	Type of fuel package[B]	n	ND (%)	Median	Range	P-value Pallet and Straw vs. Alpha OSB vs. Bravo OSB	Most protective short-term occupational exposure limit[C]
Hydrogen Fluoride (mg/m^3)	Pallet and Straw	6	0	3.84	2.97–4.72	0.01	ACGIH C: 2.00 (mg/m^3)
	Alpha OSB	3	0	1.03	0.766–1.06		
	Bravo OSB	3	0	1.93	0.500–2.31		
Hydrogen Chloride (mg/m^3)	Pallet and Straw	6	0	8.74	7.15–12.6	0.04	ACGIH C: 2.00 (mg/m^3)
	Alpha OSB	3	0	4.60	3.93–9.10		
	Bravo OSB	3	33	1.26	<0.550–6.260		

[A]Hydrogen bromide (<0.826 mg/m^3) and Phosphoric acid (<0.551 mg/m^3) were non-detect for all samples.
[B]Simulated smoke acid gas results (<0.175 mg/m^3) were non-detect for all samples. OSB scenarios also included two pallets and one bale of straw. Pallet and straw scenarios included three pallets and one bale of straw.
[C]Based on review of short-term exposure limits (STELs) or ceiling limits (C) as listed with NIOSH Recommended Exposure Limits, Occupational Safety and Health Administrations (OSHA) Permissible Exposure Limits, and or ACGIH Threshold Limit Values (TLVs)®. If no STEL or C exists, ACGIH excursion limits (5x the TLV) are provided.

Table 4. Area air concentrations of aldehyde and isocyanates inside structure by type of fuel package.

Aldehydes	Type of fuel package[A]	n	ND (%)	Median	Range	P-value pallet and straw vs. Alpha OSB vs. Bravo OSB	Most protective short-term occupational exposure limit[B]
Acetaldehyde (mg/m^3)	Pallet and Straw	6	0	79.3	51.5–135	0.03	ACGIH C: 45.0 mg/m^3
	Alpha OSB	3	0	60.7	48.0–77.6		
	Bravo OSB	3	0	291	180–419		
	Simulated smoke	6	83	<0.154	<0.137–0.620		
Acrolein (mg/m^3)	Pallet and Straw	6	0	5.38	3.53–7.24	0.03	ACGIH C: 0.230 mg/m^3
	Alpha OSB	3	0	4.85	3.60–4.97		
	Bravo OSB	3	0	60.6	10.5–71.6		
	Simulated smoke	6	100	<0.497	<0.458–0.732		
Formaldehyde (mg/m^3)	Pallet and Straw	6	0	4.61	2.89–5.59	0.04	NIOSH C: 0.123 mg/m^3
	Alpha OSB	3	0	4.45	3.77–6.52		
	Bravo OSB	3	0	35.2	13.1–36.7		
	Simulated smoke	6	100	<0.133	<0.122–0.195		
Isocyanates	**Type of fuel package**	**n**	**ND (%)**	**Median**	**Range**	**P-value pallet and straw vs. Alpha OSB vs. Bravo OSB**	**Most protective short-term occupational exposure limit**
Methyl Isocyanate (µg/m^3)	Alpha OSB	3	0	20.5	11.8–52.7	0.83	ACGIH EL: 230 µg/m^3
	Bravo OSB	3	0	35.0	10.9–166		
MDI (µg/m^3)	Alpha OSB	3	100	<0.051	<0.041–0.113	0.51	NIOSH C: 200 µg/m^3
	Bravo OSB	3	0	0.273	0.031–0.831		
Phenyl Isocyanate (µg/m^3)	Alpha OSB	3	33	<0.034	<0.015–0.041	0.83	NA
	Bravo OSB	3	0	0.033	0.019–0.120		

[A]OSB scenarios also included two pallets and one bale of straw. Pallet and straw scenarios included three pallets and one bale of straw.
[B]Based on review of short-term exposure limits (STELs) or ceiling limits (C) as listed with NIOSH Recommended Exposure Limits, Occupational Safety and Health Administrations (OSHA) Permissible Exposure Limits, and or ACGIH Threshold Limit Values (TLVs). If no STEL or C exists, ACGIH excursion limits (EL, 5x the TLV) are provided.

Table 5. VOCs air concentrations by location and type of fuel package.

VOCs	Fuel Type[B]	Location	n	ND (%)	Median	Range
Benzene[A] (ppm)	Pallet and Straw	Downwind	4	0	0.0033	0.000980–0.013
		Background	2	100	<0.000354	<0.000354
		Inside Structure	4	0	1.30	0.900–1.40
	Bravo OSB	Background	1	100	<0.000354	<0.000354
		Downwind	2	0	0.0665	0.041–0.092
		Inside Structure	2	0	2.57	0.049–5.10
	Alpha OSB	Background	1	0	0.00059	0.00059
		Downwind	2	0	0.0139	0.0098–0.018
		Inside Structure	2	0	0.0139	0.420–4.200
	Simulated Smoke	Background	2	50	0.000477	<0.000354–0.000600
		Inside Structure	4	50	0.000877	<0.000354–0.0021

[A]Benzene NIOSH STEL: 1.00 ppm
[B]OSB scenarios also included two pallets and one bale of straw. Pallet and straw scenarios included three pallets and one bale of straw.

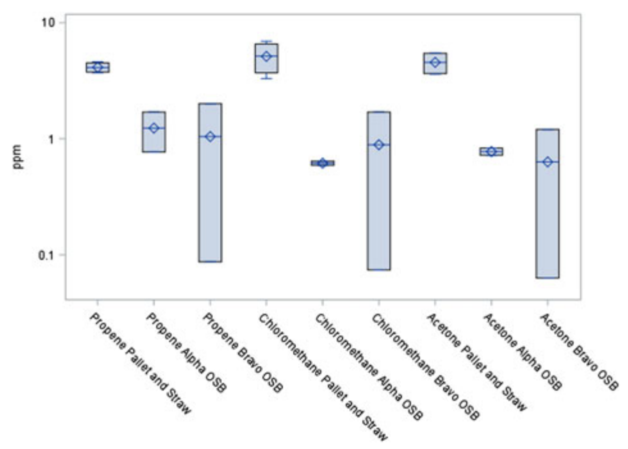

Figure 1. VOCs (ppm) area air concentrations inside structure by type of fuel package: pallet and straw (n = 4), Alpha OSB (n = 2), and Bravo OSB (n = 2). OSB scenarios also included two pallets and one bale of straw. Pallet and straw scenarios included three pallets and one bale of straw. The box and whiskers provide the minimum, 25th percentile, median, 75th percentile, and maximum values.

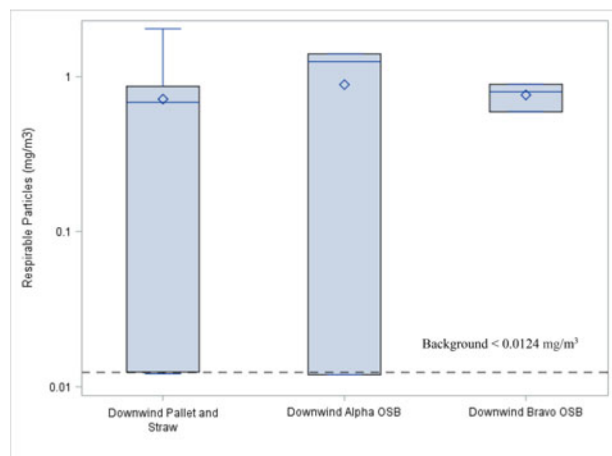

Figure 2. Downwind area air concentrations (mg/m^3) of respirable particles by type of fuel package. All background samples were non-detect. The box and whiskers provide the minimum, 25th percentile, median, 75th percentile, and maximum values.

scenarios were below detection. Interestingly, the Bravo OSB scenarios produced median air concentrations of formaldehyde, acrolein, and acetaldehyde above applicable ceiling limits that were also 4.8–12-fold higher than what was measured during the alpha OSB scenarios. Area air samples for isocyanates were only taken during the Bravo and Alpha OSB scenarios because the OSB panels were expected to contain MDI-based glues. Bravo OSB had higher median concentrations of all measured isocyanates than Alpha OSB. All concentrations of isocyanates were below their respective exposure limits (ceiling and excursion limits).

Median area air concentrations of three of the most abundant VOCs by type of fuel package are presented in Figure 1. Median concentrations of propene, chloromethane, and acetone were highest when pallet and straw were the fuel package. The VOC concentrations inside the structure were near background concentrations during the simulated smoke exercises (Supplemental Materials, Table S3). Because benzene was the most abundant VOC relative to its STEL, Table 5 provides additional information on benzene concentrations inside structure, downwind, and in the background (inside structures). Median benzene concentrations downwind were above background for all the live-fire scenarios. Benzene was highest when Bravo OSB was the fuel package, with median area air concentrations 4.8-fold higher than those measured during the alpha OSB scenario.

Figure 2 compares downwind area air concentrations of respirable particles by type of fuel package. Background concentrations of respirable particles (inside structures) were below or near detection limits. Downwind concentrations were highly variable, but median values were well above background for all live-fire scenarios. Alpha OSB had the highest median downwind concentration of 1.33 mg/m^3.

Discussion

This study provides a characterization of airborne concentrations of several chemicals during fire training scenarios commonly used in the fire service. Personal air samples were collected to allow comparisons between firefighters and instructors and between training scenarios and fuel packages. We also collected area air samples for multiple contaminants inside and downwind of the structure. The latter provides important information for personnel on the training ground who are not directly involved in the response and seldom wear SCBA.

The personal air sampling results indicate that airborne contaminants during live-fire scenarios can exceed applicable short-term occupational exposure limits, and depend largely on the participant's training ground position as well as the fuel package utilized. Table 2 compares these results to our previous residential fire study,[13] where we examined differences in airborne contaminants by fire ground job assignment and burned typical residential furnishings. Personal air concentrations of HCN in the current study were much lower (maximum = 6.96 ppm) than the residential fire study (maximum = 106 ppm) and a study by Jankovic et al.[2] (maximum = 23.0 ppm) that examined 22 fires, including 15 residential, 6 training, and 1 car fire.

The personal air concentrations of benzene measured from firefighters during the Bravo OSB scenario (median = 31.7 ppm) were similar to the residential fire study (attack firefighters median = 40.3 ppm; search firefighters median = 37.9 ppm).[13] Meanwhile, the firefighters' personal air concentrations of benzene for the other fuel packages (maximum levels ranging from 7.10–25.6 ppm) were within the ranges reported by Jankovic et al. (maximum = 22.0 ppm).[2]

We found a similar trend when examining personal air concentrations of total PAHs, whereby firefighters' concentrations during bravo OSB exercises (median = 34.0 mg/m^3) were similar to the attack firefighters (median = 23.8 mg/m^3) and search firefighters (median = 17.8 mg/m^3) in the residential fire study.[13] Personal air concentrations of total PAHs for the other fuel packages (range in medians: 2.78–8.33 mg/m^3), however, were lower than the residential fire study, but within the ranges reported previously for particleboard training fires (0.430–2.70 mg/m^3).[12]

When we stratified by type of participant, firefighters had higher personal air concentrations of every compound compared to instructors, regardless of type of fuel package. However, the instructors' sampling times were longer than firefighters' (∼25 min vs. ∼10 min), and included periods of relatively low exposure during job assignments like ignition and cleanup. These important differences in assigned activities may be the primary reason for the observed differences in personal air concentrations by participant type. Another factor that could affect these results is that firefighters completing search and rescue and fire attack jobs are typically closer to the source of the fires than the instructors, although instructors are often oriented a bit higher in the compartment. While SCBA protects firefighters from airborne contaminants, previous results suggest airborne chemicals can still be absorbed through the skin during firefighting.[19,20] Thus, efforts should be taken to reduce personal air concentrations (and the overall burden) when feasible.

According to our area air sampling results, the pallet and straw scenario produced the highest concentrations of hydrogen fluoride and hydrogen chloride of all the scenarios, with median levels above applicable ceiling limits. Hydrogen bromide and phosphoric acid were not detected in any of the scenarios. Area air samples from the residential fire study found levels of hydrogen chloride (median = 7.33 mg/m^3) that were similar to those found when pallet and straw was burned (median = 8.74 mg/m^3). Hydrogen bromide (median = 6.78 mg/m^3) results were higher in the residential fire study than those reported here, while hydrogen fluoride concentrations were lower in the residential fire study (median < 0.190 mg/m^3). The source of these halogens is unknown, especially for pallets (pinewood) and straw, but it is possible that the fuel packages were contaminated with chlorinated or fluorinated compounds from unknown treatments. Pallets used in this study were not used to transport any material between the time they were constructed and delivered to IFSI specifically for this study.

Our area air sampling results show that aldehyde concentrations were highest for the Bravo OSB exercises. Among the aldehydes assessed in this study, acetaldehyde was the most abundant and had the highest median concentration at 291 mg/m^3 during the bravo OSB scenario (exceeding its ceiling limit). Although less abundant than acetaldehyde, median concentrations of formaldehyde and acrolein were above their applicable ceiling limit for all live-fire scenarios. In another study examining aldehyde levels during emergency structure fire responses, maximum concentrations of formaldehyde (9.83 mg/m^3), acrolein

(7.34 mg/m^3), and acetaldehyde (14.6 mg/m^3)[2] were lower than the levels reported here.

Isocyanate concentrations were also highest during the bravo OSB scenarios. To our knowledge, this is the first study to quantify airborne isocyanates during training fires. Diisocyanates (e.g., MDI) are known respiratory sensitizers and exposures should be controlled to the lowest feasible levels.[21] We were not able to identify exact proportions of different adhesives in the two OSB products as this is proprietary information, but these results suggest that bravo OSB (with <0.01% free, unbounded formaldehyde) may have contained higher amounts of MDI-based adhesives than the alpha OSB (with <0.1% free, unbounded formaldehyde), as area samples during alpha OSB scenarios were non-detect for MDI. Combustion of the MDI-based adhesives could have also contributed to higher airborne concentrations of the other isocyanates and aldehydes.

Median area air concentrations of respirable particles downwind from the training structures were highest for the alpha OSB scenario, but median downwind concentrations for all live-fire scenarios were well above background (>12.7 μg/m^3). Benzene concentrations downwind of the live-fire scenarios were also above background and highest for bravo OSB (0.0665 ppm). These results are similar to the residential fire study where median benzene concentrations downwind of the structure were 0.210 ppm. These results corroborate previous findings indicating that support personnel in the fire ground can be exposed to combustion byproducts, especially when they are downwind of the structure.

Air concentrations for the majority of chemicals of interest were highest for the Bravo OSB scenarios followed by Alpha OSB, pallet, and straw, and then simulated smoke. The notable exceptions to this trend were with some of the VOCs and acid gases. While personal air concentrations of styrene, benzene, ethylbenzene, and toluene followed this trend (Supplemental Materials), some area air concentrations of other VOCs and acid gases did not. Specifically, area air concentrations of propene, chloromethane, acetone, hydrogen chloride, and hydrogen fluoride were highest for the pallet and straw scenarios. Despite these results, our overall findings suggest that burning OSB releases more airborne toxicants than pallet and straw or simulated smoke.

When comparing personal air concentrations to area air concentrations of benzene, we uncovered marked differences. Median personal air concentrations of benzene were 2–10 times higher than area air concentrations of benzene. Benzene is heavier than air (vapor density = 2.7), and may have partitioned to the lower part of the structure where the firefighters were crawling or crouching during the training.[13] Moreover, firefighters were closer to the source of contamination compared to the area air samples (located near an exterior wall). It is also possible that some of the benzene and other vapors condensed in the copper tubing leading to the evacuated canisters. However, the tubing was wrapped in insulation to minimize this effect. Regardless of the cause, the area air concentrations may not accurately represent the levels encountered by the firefighters and instructors inside the training structures.

Other limitations of this study include the high frequency of sampling pump faults and variability in training and environmental conditions that could influence the measured air concentrations. To address these limitations, personal and area air samples that did not run for at least three min of the training exercise were excluded. No testing was done to determine the efficiency of our process for cleaning tubing after each scenario. However, soap and water removed most of the loose particulate, and sampling tubing was replaced each day. Another limitation to this study is the low sample size for area air samples. However, we designed our study to ensure repeatable fuel loads and conditions over multiple days to permit comparisons between scenarios and fuel packages.

Conclusions

This study suggests firefighters and instructors operate in high concentrations of airborne contaminants during training fires that can potentially result in systemic exposures. Maximum area and personal air concentrations during the fire period of the OSB and pallet and straw scenarios were above applicable short-term occupational exposure limits for many of the measured compounds, including PAHs, benzene, acrolein, formaldehyde, and hydrogen chloride. Formaldehyde concentrations of this magnitude are noteworthy, particularly during bravo OSB scenarios where concentrations were over 280 times higher than the NIOSH ceiling limit. Efforts should be taken to minimize the use of OSB during training fires where appropriate, particularly when possible to meet training objectives without the use of this material. Area air concentrations inside the structure during the simulated smoke exercises were well below applicable exposure limits, and so, this type of training scenario would likely expose firefighters to the least amount of chemicals analyzed in this study. Chemical concentrations downwind of the training structures were above background but an order of magnitude below applicable exposure limits. When possible, efforts should be taken to position the fire apparatus and command post upwind from the burning structure. Regardless of the scenario, firefighters and instructors should wear SCBA throughout the entire training response to protect their airways, including donning SCBA before entering the structure or areas where any level of visible smoke is present (including light haze). Dermal absorption of some of the contaminants is also possible during live-fire training, and so, efforts should be taken to wear all NFPA-compliant PPE during exercises, while also cleaning skin and clothing as soon as possible post-fire. If OSB is to be used, it is suggested that training institutes should attempt to purchase OSB with the least amount of synthetic adhesives.

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