




Chemical and Thermal Exposure Risks in a Multi Compartment Training Structure

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Abstract. Providing NFPA 1403 compliant live-fire training can present thermal and chemical exposure risk to instructors and students. To reduce risk, training academies, fire departments, instructors, and standards setting technical committees need more information on how different training fuels used in common training structures can impact the environment in which firefighter training occurs. This study utilized a traditional concrete training structure with multiple compartments to characterize training environments with three different fuel package materials [i.e., low density wood fiberboard, oriented strand board (OSB), and wood pallets]. Exposure risks for a fire instructor located on either the first or second floor were characterized using measurements of heat flux, air temperature and airborne concentrations of several contaminants including known, probable, or possible carcinogens. It was hypothesized that utilizing a training fuel package with solid wood pallets would result in lower concentrations of these airborne contaminants [aldehydes, polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs)] than wood-based sheet goods containing additional resins and/or waxes. Additionally, it was hypothesized that these concentrations would be lower than in the single compartment Fire Behavior Lab presented in a companion manuscript. For all measured compounds other than hydrochloric acid, airborne concentrations were 10 to 100 times lower than in the Fire Behavior Lab. OSB-fueled fires produced the highest median concentrations of total PAHs and VOCs such as benzene, while the pallet fuel package produced the lowest median concentrations of these compounds. These trends generally followed the qualitative visual obscuration created by each fuel. Additional tests were conducted on the OSB-fueled fires with increased ventilation and an alternate means of reducing visibility through smoldering smoke barrels. This OSB experiment with increased ventilation resulted in the highest temperatures in the fire room but the lowest impact on visibility throughout the structure, as well as the lowest overall concentrations of contaminants in this study. In contrast, the smoldering straw-filled

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smoke barrel created a highly obscured environment (with minimal impact on thermal environment) and some of the highest concentrations of the targeted contaminants of any test. These data may be useful in balancing obscurity for training with potential exposure to thermal stressors and contaminants.

Keywords: Firefighter, Training fires, Occupational exposure, NFPA 1403

1. Introduction

Over the past decade, two of the most pressing Occupational Health and Safety questions in the fire service have been: (1) How to protect firefighters from carcinogenic exposures leading to increased risk of occupational cancer? (2) How to appropriately prepare firefighters for today's fireground responses in a manner that controls unnecessary exposures yet achieves the stated training objective? These questions are important because several studies have found that firefighters have increased risk for numerous types of cancer compared to the general population (e.g., [1–12]). While much effort has focused on firefighters' exposure to carcinogens during emergency fire responses (e.g., [13–24]), firefighters may also be exposed to chemical carcinogens during training fires [25–41]. In fact, a recent study found a dose–response relationship between estimated exposures from training fires and cancer incidence at a fire training college in Australia [6].

National Fire Protection Association (NFPA) 1403: Standard on Live Fire Training Evolutions outlines minimum requirements for conducting live-fire training and includes guidance so that learning objectives are achieved with the goal of mitigating health and safety hazards [42]. In Sect. 4.13, NFPA 1403 requires that fuel materials only be wood products, defining acceptable fuels (in the Appendix) as "...pine excelsior, wooden pallets, straw, hay, and other wood-based products..." [42], but the category of "other wood-based products" may include a range of materials that could have different burning characteristics. Currently, materials specifically designed for live-fire training do not exist, so the fire service typically incorporates commonly available combustibles. To support guidance provided by NFPA 1403, recent studies have documented heat release rate characteristics of common NFPA 1403-compliant training fuel packages in free burn conditions [43] and characterized thermal environments in training fire environments [44–48]. However, these training environments were created with different fuel materials and fuel orientation as well as different training structures and ventilation configurations, which complicates understanding of the fuel source alone.

Many different training fuels have been studied over the past several years, resulting in a wide range of airborne air concentrations of many different compounds [25–41]. Concentrations of products of combustion may depend on many factors, including the fuel package (materials used, amount of fuel, free surface area, orientation), training structure [layout, interior volume, number of compartments, number of stories, surface materials (metal, concrete, drywall, etc.)], combustion condition (e.g. flaming vs. smoldering), and ventilation along with duration of burn. While there are a large number of variables to consider, there are only a handful of fuels [e.g. pallets, oriented strand board (OSB), fiberboard,

particle board, plywood] and fuel orientations (ceiling mounted, loaded in a ground-based metal burn rack) that are most commonly used. By using a relatively standardized measurement methodology, researchers have started to parse the impact of the variables cited above. Two of these studies directly compared exposure of firefighters working in different training fire environments. However, in both studies, the training environments differed with respect to the fuels and the layout and compartmentation of the training structure used [29, 30, 37, 38].

Recently, thermal environments and airborne concentrations of known, probable, and possible carcinogens were characterized in a single compartment training structure known as the Fire Behavior Lab. In this metal container-based, single compartment training prop, fuel packages were mounted high on the structure walls and ceiling to achieve under-ventilated fires [41, 44]. The highest concentrations of chemical compounds measured in this study were found at the rear instructor location, followed by the front instructor location and the lowest concentrations identified at a simulated outside instructor location. However, minimal differences were found in environmental conditions measured at simulated instructor head heights (0.9 m above the floor) between five common training fuels [low density wood fiberboard (referred to as 'fiberboard'), OSB, pallets, particle board, plywood] when similar training fire environments were created. This finding, which was attributed, in part, to the ventilation configuration and fuel orientation. This fuel arrangement is typical of training fire environments created to achieve fire dynamics learning objectives (e.g. [35, 42, 44, 48]).

However, other fire service training scenarios may focus on task or skill development [45, 46]. In these scenarios, the fuel package is not necessarily intended to recreate the representative dynamic fire environment, but instead it is used to create environments where the generated air temperature and heat flux provide learning cues regarding thermal feedback and the density of smoke is controlled to provide varying levels of visual obscuration. In these cases, a common fuel package orientation is to load fuels (traditionally a combination of pallets and straw/excelsior, though other wood-based fuels such as OSB or fiberboard may also be added) onto a metal burn rack, which is elevated slightly from the ground of the training prop. Due to their lower elevation in the compartment, these fuels will typically be burned with higher local oxygen concentrations, which will produce heat and smoke throughout the structure. However, dynamic fire behavior is relatively local to the fuel and ignition location. While exposure risks from increased thermal conditions have been a concern since the advent of live-fire training, the chemical exposure risk from the smoke conditions created has more recently come into focus.

The purpose of this paper is to characterize the airborne chemical concentrations of known, probable, and possible carcinogens and thermal exposure risks for a fire instructor operating in a multicompartment training structure using three commonly available training fuels on ground-based burn rack fuel packages. It was hypothesized that utilizing a training fuel package with solid wood pallets would result in lower concentrations of these airborne contaminants [acid gases, aldehydes, polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs)] than wood-based sheet goods that contained resins and/or waxes in addition to wood fibers. Additionally, it was hypothesized that the concentra-

tions measured in this multicompartment training structure would be lower than previously reported in the single compartment Fire Behavior Lab presented due to the location of fuel packages near the ground with higher local oxygen concentrations and larger volume of the multicompartment structure.

2. Methods

A technical panel of fire service training experts from across the United States was formed to help guide method development, training fuels selection, training structure selection, sampling plan, and overall study design. Members of this panel also provided feedback on initial results and proposed additional experiments to address common fire service questions. For this series of experiments, all live-fire training burns were conducted at the North East Regional Training Center of the Maryland Fire Rescue Institute (MFRI) in Gunpowder, Maryland (USA).

2.1. Study Design

This study was designed to characterize the training fire environment (thermal conditions and gas concentrations) produced by utilizing three different wood-based products commercially available in the USA in a multiple compartment, concrete structure purposely designed and built for live-fire training in the USA. The three different wood-based products (fiberboard, OSB, and pallets identical to those used in [41, 44]) and straw were utilized in these fuel packages. Five replicate experiments were conducted with each fuel package. The order of introduction followed a block randomization scheme with three experiments per block (i.e. each of the three fuels was used in the first three experiments, then reordered for the next three experiments, etc.) to reduce any bias from changing environmental conditions when using the outdoor training structure. Five additional exploratory experiments were conducted: (1) OSB and straw with additional ventilation, (2) pallets with excelsior instead of straw, (3) OSB with excelsior instead of straw, (4) smoke barrel filled with straw and (5) smoke barrel filled with excelsior.

2.2. Test Structure and Fuel Package

Live-fire training environments were created in a two-storey, five room concrete training structure with a three-storey stairwell connecting hallways on the first and second floor (Fig. 1). The test structure had a total smoke filling enclosed volume of 347.5 m³. The training fuels utilized in this structure were loaded on two separate metal burn racks that were slightly elevated from the concrete floor of the fire room (Fig. 2). In a typical training evolution, firefighters and instructors move through the structure and apply water to burning fuel while oversight instructors and safety officers remain inside the building throughout the evolution and clean up. This study focused on the likely highest exposure group of individuals involved in these training exercises by monitoring concentrations of airborne compounds in the location where safety instructors would typically be located.



Figure 1. Multicompartment training structure at the Maryland Fire Rescue Institute. (Left) front view with burn room on the left and hallway in the middle. (Right) side view showing burn room, stairs to second floor landing above the burn room and three-storey stairwell.



Figure 2. Fuel loads for replicate experiments with (left) pallets and straw, (center) OSB, pallets and straw, and (right) fiberboard, pallets and straw.

2.2.1. Replicate Fuel Packages To simplify identification of fuel packages, *Pallet* refers to fuel loads with four pallets in a triangle set (two pallet base, two pallets lean-to and wired together; no additional sheet goods), *OSB* refers to a fuel load with one sheet of OSB attached to the outside of a three pallet triangle set (half sheet on each of the two lean-to pallets), and *Fiberboard* refers to a fuel load with a total of two sheets of fiberboard attached to the outside of a three pallet triangle set (two half sheets on each of the two lean-to pallets, Fig. 2). All sheet materials used were approximately 1.2 m 1.2 m 11 mm to 13 mm thick. A half bale of straw was fluffed in the area between the lean-to pallets. The fuel package for these experiments consisted of two identical fuel loads on two separate burn racks in the fire room. Before each experiment, the total fuel package mass was measured using a digital scale (Table 1), though it should be noted that not all materials were consumed by the completion of each experiment.

Each fuel package consists of two identical fuel loads on two separate burn racks in the fire room. For example, the Fiberboard fuel package includes a total of six pallets, four sheets of Fiberboard and one bale of straw while the Pallets fuel package includes a total of eight pallets and one bale of straw.

Table 1
Total Fuel Package Component Mass by Material Type

	Component Mass (kg)				
	Pallets	Straw	OSB	Fiberboard	Excelsior
Replicate Experiments					
Fiberboard	90.6 (1.6)	14.4 (1.1)	—	32.5 (0.2)	—
OSB	92.4 (2.6)	15.2 (1.0)	41.8 (0.4)	—	—
Pallets	126.6 (1.6)	14.1 (0.4)	—	—	—
Exploratory Experiments					
OSB Extra Vent	99.2	13.4	41.8	—	—
OSB/Excelsior	94.1	—	41.8	—	12.9
Pallets/Excelsior	127.2	—	—	—	12.9
Straw	4.6	5.9	—	—	—
Excelsior	4.6	—	—	—	5.9

For replicate experiments, data are presented as mean (standard deviation) from five experiments

2.2.2. Fuel Packages for Exploratory Tests Based on guidance from the project technical panel, five additional exploratory tests were conducted to study the impact of slight changes in ventilation using the *OSB* fuel package (opening a single Fire Room window and exterior door on second floor), substituting straw for a similar mass of excelsior in the *Pallet* and *OSB* fuel loads (Fig. 3a, b) and utilizing straw or excelsior in a smoke barrel without a fire set as a common approach to increasing visual obscuration without adding to the thermal burden (Fig. 3c, d). For the smoke barrel experiments, all interior doors were closed, one barrel was placed in the middle of the first-floor hallway and another in the middle of the second-floor hallway. Following common protocol, small pieces of pallet were inserted at the bottom of the barrel to maintain smoldering combustion as the straw/excelsior was consumed. The straw was wetted with water by separate instructors on each floor with the goal of maintaining mostly smoldering, non-flaming fires with heavy smoke production. Small ventilation holes were located near the bottom of the barrel where the straw/excelsior was ignited.



Figure 3. Fuel loads for exploratory experiments with (from left to right) pallets and excelsior; OSB, pallets and excelsior; smoke barrel with wetted straw; and smoke barrel with wetted excelsior.

2.3. Thermal Measurements

The training structure was instrumented with thermocouples, heat flux gauges, pressure transducers, and environmental gas sampling. The instrument locations were chosen as representative of areas where instructors/safety officers would be situated throughout a training scenario on the first floor and second floor as well as in the Fire Room and end of the second floor hallway (Fig. 4, with detailed isometric drawings shown in Figs. S1–S4 of Supplemental Materials).

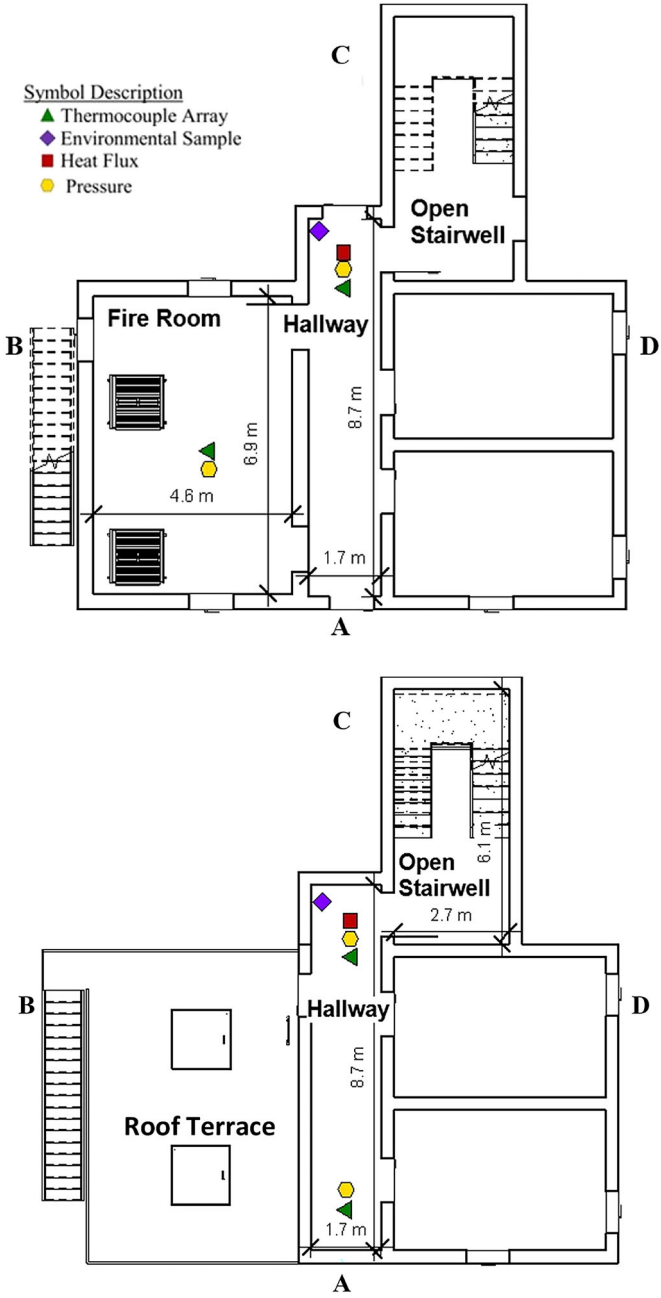
Gas temperatures were measured with 0.5 mm diameter bare-bead, type K thermocouples arranged at all four measurement locations in vertical arrays of eight thermocouples, spaced 0.3 m apart between 0.3 m and 2.4 m above the floor. Ceiling height varied throughout the structure; 2.7 m in the fire room, 2.8 m in the first floor hallway, and 3.1 m in the second floor hallway. The estimated total expanded uncertainty associated with the temperature measurements is $\pm 15\%$ [49, 50]. Small diameter thermocouples were utilized to limit the impact of radiative heating.

Total heat flux measurements were obtained with nominal 25 mm diameter, water-cooled Schmidt-Boelter gauges co-located with the environmental sampling locations. At each measurement location, two heat flux gauges were located approximately 0.9 m above the floor; one was oriented in the horizontal direction (towards the fire area) and the other in the vertical direction (towards the ceiling). Results from an international study on total heat flux gauge calibration and response demonstrated the total expanded measurement uncertainty of a Schmidt–Boelter gauge is typically $\pm 8\%$ [51].

This manuscript is focused on measurements collected 0.9 m above the ground, which was the assumed height of a firefighter/fire instructor at crouching or crawling level. If safety officers would be standing and therefore oriented higher in the structure, they would likely have higher thermal and chemical exposures [41, 44].

2.4. Area Gas Sampling

The area gas sampling strategy used identical methods as Horn et al. [41], which built off the work of Fent et al. [37] and provides one of the most complete characterizations of compounds measured during live-fire training in literature. Table 2 provides a summary of the area gas sample collection including sampling media, flow rates, and analysis methods utilized to characterize 1, 3-butadiene, aldehydes, aromatic hydrocarbon volatile organic compounds (VOCs), hydrogen chloride (HCl), methyl isocyanate, and polyaromatic hydrocarbons (PAHs). The VOC sampling method focused on benzene, toluene, ethyl benzene, xylenes, and styrene (BTEXS), and the aldehyde sampling methods targeted formaldehyde, acetaldehyde, and acrolein. HCl and methyl isocyanate are not classified as carcinogens by the International Agency for Research on Cancer (IARC) but have been reported in previous studies of firefighter exposure and are important to include because both are severe respiratory irritants. Reporting limits (RL) provided by the analytical laboratory are also included in Table 2. Non-detectable measurements are reported in the results tables as $<RL/sample\ volume$ (i. e., minimum detectable concentration). These minimum detectable concentrations may vary from one measurement to the next because the total volume of gas col-



◀Figure 4. Multicompartment training structure layout and sampling locations on the first floor (top) and second floor (bottom). The air sampling cluster of instruments at the end of the C-side hallway are representative of first- and second-floor safety/instructor staging areas. Labeling of the sides of the building are consistent with typical fire service protocol, that is, A being the front or address side, then subsequent sides are labeled B, C, and D in a clockwise rotation.

lected for each analyte during each experiment will vary slightly based on individual pump run times and actual flow rates.

Sampling media were located at the first- and second-floor instructor locations, roughly 0.9 m above the floor as an approximation of the head height of a kneeling or crouching instructor (Fig. 4). Sampling pumps [Gilian BDX-II (Sensidyne, St Petersburg, FL) or PCXR4 Universal sample pumps (SKC, Eighty Four, PA)] were calibrated to within 5% of the target flow rate outlined in Table 2. Post fire flow rates were typically within $\pm 5\%$ of the initial calibrated value, though 16 of the 126 samples varied by $\pm 5\%$ to 7% and two by more than 9%. All media were stored in either a refrigerator and/or freezer as appropriate (per analytical method described in Table 2) prior to sampling and prior to shipment (on ice) to the analytical laboratory under chain of custody. Details on precision, accuracy and/or bias for each sampling/analytical method employed can be found in method documentation [52–55]. Laboratory control spikes were included to test that recoveries were within the method limits, and results were recovery corrected to improve accuracy and reduce bias.

Table 2
Area Gas Sample Collection and Analysis Methods

Compound	Sampling media	Average flow rate (L/min) ^a	Analytical method	Reporting limit, RL (g)
1, 3-Butadiene	SKC 226-09 Charcoal tube 600 mg	0.25	NIOSH 1024 [52]	1.0
Aldehydes (Formaldehyde; Acetaldehyde; Acrolein)	SKC 226-117 Treat XAD for Ald-GC	0.1	OSHA 52/ OSHA 68 mod. [53, 54]	Form 1.0; Ace 2.0; Acr 2.0
BTEXS (Benzene; Toluene; Ethyl-benzene; Xylene; Styrene)	SKC 226-01 Charcoal tube 150 mg	0.2	NIOSH 1501 [52]	B 1.0; T 2.0; E 2.0; X 4.0; S 10
Hydrogen Chloride (HCl)	SKC 226-10-03 Silica gel 400/200 mg w/glass fiber filter plug	0.2	NIOSH 7903 [52]	5.0
Methyl Isocyanate	Asset EZ4-NCO	0.5	ISO 17734 [55]	0.015
Polycyclic Aromatic Hydrocarbons (PAHs)	Zefon XAD-7	1.0	NIOSH 5528 [52]	0.10 for each PAH

ISO International Organization for Standardization, NIOSH National Institute for Occupational Safety and Health, OSHA Occupational Safety and Health Administration

^aSamples collected over 14 min period inside the training structure (12 min ignition to suppression, 2 min post suppression) with a few additional minutes pre and post fire for start up and shut down procedure

Although there exist hundreds of known PAHs, the US Environmental Protection Agency (EPA) has designated 16 as High Priority Pollutants because of their potential toxicity as well as their prevalence and persistence in the environment. The 16 EPA priority PAHs include acenaphthylene (Acy), acenaphthene (Ace), anthracene (An), fluoranthene (Fla), fluorene (Fl), benzo[a]anthracene (BaA), benzo[a]pyrene (BaP), benzo[b]fluoranthene (BbF), benzo[g, h, i]perylene (BghiP), benzo[k]fluoranthene (BkF), chrysene (Ch), dibenzo[a, h]anthracene (DBA), indeno[1, 2, 3-cd] pyrene (IP), naphthalene (Nap), phenanthrene (Ph), and pyrene (Py). PAH data is reported using linear combinations of the compounds including:

(A) total PAHs (Σ PAH),

$$\begin{aligned} \sum PAH = & [Ace] + [Acy] + [An] + [BaA] + [BaP] + [BbF] + [BghiP] \\ & + [BkF] + [Ch] + [DBA] + [Fl] + [Fla] + [IP] + [Nap] + [Ph] + [Py], \end{aligned} \quad (1)$$

(B) percentage of total PAH that were known, probable or possible carcinogens based on IARC classification of Group 1, 2A, or 2B, respectively (Σ PAH_{carc}/ Σ PAH),

$$\begin{aligned} & \frac{\sum PAH_{carc}}{\sum PAH} \\ & = \left(\frac{([BaA] + [BaP] + [BbF] + [BkF] + [Ch] + [DBA] + [IP] + [Nap])}{\sum PAH} \right) * 100, \end{aligned} \quad (2)$$

(C) benzo[a]pyrene-relative toxicity equivalence (BaP_{TEQ}),

$$\begin{aligned} BaP_{TEQ} = & 0.001 * ([Ace] + [Acy] + [Fla] + [Fl] + [Nap] + [Ph] + [Py]) \\ & + 0.01 * ([An] + [Ch] + [BghiP]) \\ & + 0.1 * ([BaA] + [BbF] + [BkF] + [IP]) \\ & + 1 * [BaP] + 5 * [DBA], \end{aligned} \quad (3)$$

(D) benzo[a]pyrene-relative mutagenic equivalence (BaP_{MEQ}),

$$\begin{aligned} BaP_{MEQ} = & 0.00056 * [Acy] + 0.082 * [BaA] + 1 * [BaP] + 0.25 * [BbF] \\ & + 0.19 * [BghiP] + 0.11 * [BkF] + 0.017 * [Ch] \\ & + 0.29[DBA] + 0.31[IP]. \end{aligned} \quad (4)$$

The values of weighting parameters used in Eqs. 3 and 4 were presented in Nisbet and LaGoy (1992) and Durant et al. [56, 57]. For compounds that were not

detected in concentrations above the limit of quantitation, the value of the reporting limit divided by square root of two was used in these calculations [58].

2.5. Experimental Protocol

At the beginning of each day of experiments, background (pre-fire) area gas samples were collected for 30 min in the observation area.

All exterior windows and doors (other than that used by the instructors) were closed as were interior doors from the hallways into the rooms other than the fire room (Fig. 4). Two minutes prior to ignition, sampling pumps (located inside insulated cabinets) were turned on and sampling media (with the inlet extending just outside the insulated cabinet) were simultaneously exposed at locations that represented where instructors/safety officers would be located at the first and second floor of the training structure.

Two instructors simultaneously ignited the straw (or excelsior when used) at the base of both fuel loads and immediately left the structure, closing the exterior door behind them. Smoke flowed out of the fire room, filled the stairwell as well as the first- and second-floor hallway, and naturally leaked out of gaps around windows and doors throughout the structure. Fires were allowed to grow without further instructor intervention but with some variability based on how pallets fell as they were consumed by the fire. Twelve minutes after ignition, the Side A window on the first floor was opened, and both fire sets were suppressed from the exterior to allow for a consistent burn and smoke filling time that was similar to Fent et al. [37] and the three-cycle experiments reported by Horn et al. [41]. This time was deemed typical for how this structure would be used from ignition to the time firefighters would enter and suppress fires for typical coordinated attack training scenarios as in Fent et al. [37].

Two minutes after suppression was complete, firefighters entered the training structure to remove the sampling pumps. Sampling pumps were immediately turned off, sampling media were capped, and stop time was recorded. The timing of when the media was exposed and capped was recorded for each location.

At completion of the experiments, the burn room was cleaned out with a shovel and broom. After cooling, a blower was used to remove any remaining loose materials prior to reloading with new training fuel. Two or three separate experiments were conducted on each of eight separate days of experiments with a minimum of two hours between each experiment.

2.6. Data Analysis

Descriptive statistics are presented as median and range for all variables, stratified by fuel package. For hypothesis testing, time averaged thermal measures and gas concentrations were compared across each of the three fuel packages using the Kruskal–Wallis test. Where significant effects were detected, post hoc Mann–Whitney U-test were conducted to compare data from pairs of fuel packages directly. All statistical tests were two-sided at the 0.05 significance level.

Airborne gas concentrations collected in this multicompartment concrete training structures from three fuel packages utilized were compared to values reported

from similar experiments (i.e. same sample collection and analysis methods at same height from the floor) conducted in a single-compartment metal container-based training prop with fuel packages were mounted high on the structure walls and ceiling to achieve under-ventilated fires [41]. Additionally, these values are compared to applicable short term exposure limits (STEL, based on 15-min time-weighted average concentration) and ceiling limits/excursion limits (maximum value that cannot be exceeded for any length of time) for compounds where these limits exist. These exposure limits are applicable for inhalation routes of exposure, which can be controlled through strict self-contained breathing apparatus (SCBA) usage. However, firefighters' exposure to these compounds may occur through inhalation when respiratory protection (particularly SCBA) is not worn such as when operating outside of a structure or when dislodged or temporarily removed.

3. Results

3.1. Replicate Fuel Experiments

3.1.1. Thermal Conditions Time-averaged (mean) and peak air temperatures and heat fluxes in the fire room and at the first- and second-floor instructor locations provide a means of assessing the impact of adding wood-based sheet goods to the *Pallet* fuel package (Tables 3, 4). Although trends in median data can be identified, there is considerable overlap in the range of data from most thermal measurements. In the fire room, the *OSB* fuel packages typically resulted in the highest time-averaged and peak temperatures, particularly at the ceiling. The *Pallet* fuel package consistently resulted in the lowest median temperatures and heat fluxes compared to the *OSB* and *Fiberboard* fuel packages, with a larger magnitude of difference between values from the first-floor sampling location compared to the second-floor location. However, fuel package had a statistically significant impact on time-averaged values only for fire room ceiling temperature ($p = 0.032$). Post hoc analysis identified significant differences only between the *OSB* and *Pallet* fuel packages in the fire room ($p = 0.027$).

Regardless of fuel package used, first-floor temperatures and heat fluxes at the instructor locations were considerably higher than those from the second floor due to the proximity to the fire room.

Visual obscuration was not quantified in this study, but qualitatively, the smoke produced by the *Pallet* fuel package provided the typical visual obscuration noted by authors who have several decades of live-fire training experience with similar fuel packages. Adding the sheet goods to the pallets increased smoke production, particularly early in the fire growth. Qualitatively, the *OSB* fuel package created the most dramatic visual obscuration, followed by the *Fiberboard* and then the *Pallet* fuel packages. Instructors may choose to create environments with different levels of visual obscuration based on stated training objectives and varying the fuel package materials can provide a limited means for controlling this variable.

3.1.2. Airborne Contaminant Concentrations Total PAH concentrations and calculated toxic equivalents (Table 5) were similar on the first and second floor for a

given fuel package. For all summary calculations of the PAHs, the *Pallet* fuel package was consistently the lowest, on both the first and second floor. The *OSB* fuel package resulted in the highest PAH total and toxic equivalences on both the first and second floor, though there was considerable overlap in the range of PAH data between the *OSB* and *Fiberboard* fuel packages on the second floor. Fuel package had a statistically significant impact on total PAH concentrations on the first floor ($p = 0.027$) but not the second floor ($p = 0.076$). Post hoc analysis identified significant differences only between the *OSB* and *Pallet* fuel packages ($p = 0.021$). The percentage of total PAHs that were known, probable, or possible carcinogens was also impacted by fuel package ($p = 0.013$) on both floors, with the *Pallet* fuel package being significantly lower than the *Fiberboard* ($p = 0.012$) and *OSB* ($p = 0.021$) fuel packages on both floors, but with no statistically significant difference between the *Fiberboard* and *OSB* fuel packages.

For *Fiberboard* and *OSB* fuel packages, total PAH concentrations measured inside the structure regularly exceeded the OSHA 8-h time-weighted average permissible exposure limit (PEL) and American Conference of Governmental Industrial Hygienists (ACGIH) excursion limit for “coal tar pitch volatiles” as they are currently classified for workplace standards and regulations (0.2 mg/m^3 and 1 mg/m^3 , respectively). However, median values for the *Pallet* fuel packages were

Table 3
Median and Range of Air Temperatures and Heat Fluxes at the Fire Room and Instructor Locations Time-Averaged over Experimental Durations with Each Fuel Package

	First Floor		Second Floor	
	Median	Range	Median	Range
Fire Room Ceiling Temperature (°C)				
Fiberboard	432	404–485		
OSB	455	435–506		
Pallets	400	362–448		
Fire Room 0.9 m Temperature (°C)				
Fiberboard	199	177–243		
OSB	204	176–234		
Pallets	179	131–208		
Instructor Temperature (°C)				
Fiberboard	82	72–89	47	46–48
OSB	83	72–90	49	45–50
Pallets	76	65–81	45	45–48
Instructor Heat Flux—Horizontal (kW/m^2)				
Fiberboard	2.4	1.9–2.8	0.5	0.4–0.6
OSB	2.5	2.2–2.8	0.6	0.5–0.6
Pallets	1.8	1.3–2.5	0.4	0.3–0.6
Instructor Heat Flux—Vertical (kW/m^2)				
Fiberboard	2.1	1.6–2.4	0.5	0.4–0.6
OSB	2.2	1.9–2.4	0.6	0.5–0.6
Pallets	1.7	1.2–2.2	0.4	0.3–0.6

Table 4
Median and Range of Peak Air Temperatures and Heat Fluxes in the Fire Room and at Instructor Locations from Experiments with Each Fuel Package

	First Floor		Second Floor	
	Median	Range	Median	Range
Fire Room Ceiling Temperature (°C)				
Fiberboard	571	544–608		
OSB	581	571–612		
Pallets	549	506–606		
Fire Room 0.9 m Temperature (°C)				
Fiberboard	327	310–384		
OSB	319	269–373		
Pallets	268	250–297		
Instructor Temperature (°C)				
Fiberboard	130	122–143	60	59–63
OSB	125	108–142	61	60–64
Pallets	113	103–119	57	53–59
Instructor Heat Flux—Horizontal (kW/m ²)				
Fiberboard	5.1	4.0–6.1	1.1	1.0–1.6
OSB	5.2	4.9–5.9	1.4	1.4–1.6
Pallets	4.0	3.5–5.2	1.1	0.7–1.3
Instructor Heat Flux—Vertical (kW/m ²)				
Fiberboard	4.6	3.6–5.7	1.2	1.0–1.5
OSB	4.8	4.2–5.7	1.4	1.3–1.5
Pallets	4.2	3.1–4.7	1.0	0.8–1.5

slightly below this excursion limit. Known, probable, or possible carcinogenic PAHs typically comprised between 65 and 80% of total PAHs, with naphthalene (IARC Group 2B) being the largest contributor (56% to 77% of Total PAHs). The trends in benzo(a)pyrene equivalent toxicity and mutagenicity estimates were similar to the total PAH trends, with the *Fiberboard* and *OSB* fuel package experiments resulting in the highest median quotients and the *Pallet* fuel package experiments with the lowest.

Airborne concentrations of all other compounds sampled for and detected in this study are included in Table 6. Benzene (IARC Group 1) and toluene (IARC Group 2B) were the only BTEXS compounds measured above the method detection limit at both sampling locations, thus, ethyl benzene, xylene, and styrene will not be discussed further. Benzene concentrations at both interior locations were four to nine times the NIOSH short term exposure limit (STEL) of 3.2 mg/m³ (1 ppm) for the *Fiberboard* and *OSB* fuel packages. Though concentrations were nearly an order of magnitude lower with the *Pallet* fuel package, they remained near this exposure limit. Median levels of toluene were below detection limits for the *Pallet* fuel package but were above detection with the *Fiberboard* and *OSB* fuel packages. 1, 3-Butadiene, another VOC included in IARC Group 1, was present at lower concentrations relative to its OSHA permissible exposure limit (PEL)

STEL (11.0 mg/m³). Few differences were noted between the distribution of 1, 3-butadiene concentrations from the three different fuel packages or from the first and second floors. Of the VOCs studied, fuel package had a statistically significant impact only on benzene concentrations on the first ($p = 0.008$) and second floor ($p = 0.041$). Post hoc analysis identified significant differences between both the *Fiberboard* and the *OSB* fuel packages compared to the *Pallet* fuel package ($p = 0.012$ each) on the first floor, but only between the *OSB* fuel package and *Pallet* fuel package ($p = 0.021$) on the second floor. There were no statistically significant differences between the *Fiberboard* and *OSB* fuel packages at either location.

Of the three aldehydes analyzed, acetaldehyde was typically detected in the highest concentration, with *OSB* fuel packages having the highest median values (though there was considerable overlap in the distribution of the data between each fuel package). Formaldehyde (IARC Group 1) was regularly measured at an order of magnitude above the NIOSH STEL [0.123 mg/m³ (0.1 ppm)] at both sampling locations. The distribution of formaldehyde concentrations overlapped considerably for all training fuels, though median values were typically lowest for the *Pallet* fuel package. Acrolein concentrations were also frequently above the

Table 5
Summary Polycyclic Aromatic Hydrocarbon (PAH) Results at the First- and Second-Floor Instructor Location Located 0.9 m from the Floor

	First Floor		Second Floor	
	Median	Range	Median	Range
Σ PAH (mg/m ³)				
Fiberboard	1.6	1.3–3.2	1.8	1.6–3.9
OSB	3.0	0.8–8.2	1.9	0.8–9.9
Pallets	0.7	0.3–2.1	0.6	0.3–2.4
Σ PAH _{carc} / Σ PAH				
Fiberboard	78.0%	76.2–80.0%	78.5%	78.0–79.4%
OSB	79.1%	73.5–79.1%	79.5%	73.6–80.4%
Pallets	67.6%	64.5–74.6%	67.2%	64.1–75.2%
BaP _{TEQ}				
Fiberboard	0.031	0.028–0.045	0.035	0.029–0.053
OSB	0.040	0.028–0.108	0.035	0.027–0.136
Pallets	0.028	0.026–0.043	0.029	0.027–0.049
BaP _{MEQ}				
Fiberboard	0.014	0.011–0.032	0.020	0.012–0.042
OSB	0.025	0.009–0.101	0.017	0.009–0.130
Pallets	0.010	0.009–0.034	0.010	0.009–0.040

Five samples (N = 5) were collected for each fuel and location

Σ PAH total concentration of PAHs

Σ PAH_{carc}/ Σ PAH percentage of total PAHs that were known, probable or possible carcinogens based on IARC classification of Group 1, 2A or 2B

BaP_{TEQ} toxic equivalent based on benzo(a)pyrene-relative toxicity equivalence factors

BaP_{MEQ} mutagenic equivalent based on benzo(a)pyrene-relative minimum mutagenic concentrations

For compounds that were not detected in concentrations above the limit of quantitation, the value of the reporting limit divided by square root of 2 was used in these calculations (see Table S.1)

NIOSH STEL [0.7 mg/m^3 (0.3 ppm)], and *Fiberboard* fuel package consistently generated lower concentrations than the other two fuel packages (though again there was considerable overlap in the distribution). The fuel package employed did not have a statistically significant impact on aldehyde concentrations at either location.

The range of gas concentrations of HCl overlapped for all three fuel packages, though they were typically higher for the *OSB* fuel packages. The majority of the measurements on both the first and second floors exceeded the OSHA PEL Ceiling limit (7 mg/m^3). These values for HCl are consistently higher than Horn et al. [41] reported from the Fire Behavior Lab training prop and both OSB scenarios reported by Fent et al. [37]. However, the HCl measurements from the *Pallet* fuel package was similar to the HCl measurements during pallet and straw scenarios reported by Fent et al. (2019) (7.6 mg/m^3 to 13 mg/m^3 compared to 7.2 mg/m^3 to 12.6 mg/m^3). Fuel package did not have a statistically significant impact on HCl concentrations at either sampling location.

In more than half of the samples collected, concentrations of methyl isocyanate were below the detection limit, and all samples collected were one to two orders of magnitude below the ACGIH excursion limit (230 g/m^3).

3.2. Exploratory Comparison Experiments

Data from each exploratory experiment were compared to the distribution of the data from the replicate experiments presented above. Gas temperatures and heat fluxes in the fire room, first-floor instructor location, and second-floor instructor location are included in Table 7. Airborne concentrations of PAHs and all other measured compounds are included in Tables 8 and 9, respectively.

3.2.1. OSB with Extra Vent During the *OSB* fuel package scenario with extra ventilation, the time-averaged fire room ceiling temperatures were the highest of any test conducted and the heat flux at the second-floor simulated instructor location was nearly three times greater than the highest recorded with the vents closed. However, this experiment resulted in the lowest chemical concentrations of most of the compounds collected, including total PAHs. In fact, total PAHs were seven to eight times lower than the minimum value of the distribution of the *OSB* fuel package with the vents closed. Of the 16 PAHs sampled, only naphthalene and phenanthrene were detected. The only other compound that was detectable at both locations was HCl, which was 2.4 to 5.4 times lower than the minimum concentration measured with the *OSB* fuel package and vents closed.

3.2.2. Replacing Straw with Excelsior All data from the *OSB* fuel package with excelsior in place of straw experiment lie within the distribution of the data from the five *OSB* fuel package with straw experiments, except for HCl. The time-averaged thermal conditions in the *Pallet* fuel package with excelsior in place of straw experiment were lower than the five replicate *Pallet* fuel package with straw experiments; because the fire involved a relatively small portion of the pallets when excelsior was used. It is likely that smoke produced through smoldering in this

Table 6
Benzene, Toluene, 1, 3-Butadiene, Formaldehyde, Acetaldehyde, Acrolein, Hydrochloric Acid, and Methyl Isocyanate Concentrations at the First- and Second-Floor Instructor Location, 0.9 m from the Floor

	First Floor		Second Floor	
	Median	Range	Median	Range
Benzene (mg/m ³)				
Fiberboard	13	11–31	17	<0.3–35
OSB	28	5.2–58	28	5.7–71
Pallets	3.2	2.0–4.9	2.5	<0.3–7.5
Toluene (mg/m ³)				
Fiberboard	0.60	<0.57–1.4	0.80	<0.57–1.5
OSB	1.1	<0.58–3.5	0.84	<0.58–4.2
Pallets	<0.56	<0.55–0.66	<0.59	<0.55–2.9
1, 3 Butadiene (mg/m ³)				
Fiberboard	0.27	<0.23–0.51	0.40	<0.23–0.56
OSB	0.37	<0.24–0.80	0.44	<0.23–0.98
Pallets	0.31	<0.23–1.00	0.29	<0.23–1.60
Formaldehyde (mg/m ³)				
Fiberboard	4.9	2.5–7.1	4.9	2.7–8.5
OSB	4.6	2.0–12	5.7	1.1–15
Pallets	3.7	3.4–8.7	4.7	1.6–8.0
Acetaldehyde (mg/m ³)				
Fiberboard	5.7	4.9–11	8.5	5.5–12
OSB	9.9	3.4–19	13	5.4–29
Pallets	8.5	4.6–14	6.8	5.5–17
Acrolein (mg/m ³)				
Fiberboard	1.7	1.3–3.0	2.0	1.3–3.2
OSB	2.7	<1.1–4.8	2.8	<1.2–5.8
Pallets	2.2	1.1–3.8	3.0	1.3–3.5
Hydrochloric Acid (mg/m ³)				
Fiberboard	10	5.3–14	11	5.5–15
OSB	12	10–17	13	12–20
Pallets	9.3	7.6–12	9.8	9.1–13
Methyl Isocyanate (g/m ³)				
Fiberboard	<1.8	<1.7–2.4	<1.8	<1.7–2.4
OSB	1.9	<1.7–5.4	<1.9	<1.7–4.6
Pallets	<1.8	<1.7–<1.9	<1.7	<1.7–<1.9

Five samples (N = 5) were collected for each fuel. Results shown with the less than symbol (<) are below the reporting limit (RL) and the value provided is RL divided by volume of gas collected

exploratory scenario was a relatively larger component of overall smoke production compared to the replicates with straw (additional excelsior was not added to the fire to sustain flaming combustion in order to study this unique condition). Relative to the distribution of concentrations from the *Pallet* fuel package with straw, this condition produced concentrations above maximum values for benzene, 1, 3-butadiene and BaP_TEQ as well as near maximum values for toluene, formaldehyde, and total PAHs. HCl was not detected in either scenario at either

location with excelsior despite its high concentrations in the equivalent straw experiments.

3.2.3. Smoke Barrels Thermal conditions that resulted from both smoke barrel experiments were similar to ambient conditions and were the lowest of any experiment conducted. Qualitatively, for both smoke barrel experiments, there was additional reduced visibility on the second floor compared to the first floor and more so with the straw fuel than the excelsior fuel. These smoke barrel scenarios resulted in some of the highest concentrations of 1, 3 butadiene on both the first and second floors.

Of the 20 experiments conducted, the second-floor sampling location in the straw smoke barrel experiment had the highest overall concentrations of toluene, 1, 3 butadiene (7.5 times higher than the peak value in Table 6), acetaldehyde, and acrolein. For this experiment where the fuel is almost exclusively smoldering straw, total PAHs were 2.4 times higher than the ACGIH excursion limit for coal tar pitch volatiles (1 mg/m^3), benzene concentrations were 5.3 times higher than NIOSH STEL of 3.2 mg/m^3 (1 ppm), 1, 3 butadiene concentrations exceeded OSHA PEL STEL (11.0 mg/m^3), formaldehyde concentrations were 105 times higher than NIOSH STEL [0.123 mg/m^3 (0.1 ppm)], and acrolein concentrations were 11 times higher than NIOSH STEL [0.7 mg/m^3 (0.3 ppm)].

3.3. Background Airborne Concentrations

Background samples collected in the morning of each of the eight training fire experiment days resulted in detectable levels only for benzene (2.1 mg/m^3 on Day 3), toluene (0.52 mg/m^3 on Day 6 and 0.23 mg/m^3 on Day 7), and naphthalene (0.0037 mg/m^3 to 0.0053 mg/m^3 on Days 1 to 3). The background naphthalene concentration was two orders of magnitude below typical levels detected during live-fire experiments. The source of these intermittent background emissions was not determined as part of this study but are likely due to residual off gassing from training materials that were not fully removed from previous fires. Background concentrations were not subtracted from measurements collected during training fire experiments reported in Sects. 3.1 and 3.2.

4. Discussion

4.1. Thermal Environment and Qualitative Discussion of Fire Dynamics

The instructor sampling locations were exposed to less severe conditions when using similar training fuel materials in the multi-compartment concrete training structure compared to the temperatures reported by Stakes et al. in a single compartment, metal container-based Fire Behavior Lab [44]. First floor temperatures measured in the multi-compartment structure at the instructor location with *Pallet*, *OSB*, and *Fiberboard* fuel packages (medians 76°C to 83°C) were lower than those from the Fire Behavior Lab front instructor location (medians 87°C to 102°C). Likewise, the second-floor instructor location temperatures (medians 45°C to

Table 7
Time-Averaged Mean and Peak Air Temperatures and Heat Fluxes
from the Fire Room and Instructor Locations During the Exploratory
Experiments

	Mean		Peak	
	First Floor	Second Floor	First Floor	Second Floor
Fire Room Ceiling Temperature (°C)				
OSB Extra Vent	515		600	
OSB/Excelsior	478		575	
Pallets/Excelsior	266		594	
Straw	34		34	
Excelsior	33		34	
Fire Room 0.9 m Temperature (°C)				
OSB Extra Vent	202		300	
OSB/Excelsior	209		313	
Pallets/Excelsior	81		178	
Straw	32		32	
Excelsior	32		32	
Instructor Temperature (°C)				
OSB Extra Vent	45	36	88	85
OSB/Excelsior	80	47	120	57
Pallets/Excelsior	45	36	67	41
Straw	28	30	29	33
Excelsior	28	31	30	34
Instructor Heat Flux—Horizontal (kW/m ²)				
OSB Extra Vent	1.8	1.5	3.5	3.4
OSB/Excelsior	2.4	0.6	4.8	1.2
Pallets/Excelsior	0.5	0.2	1.7	0.4
Straw	0.1	0.1	0.2	0.2
Excelsior	0.1	<0.1	0.2	0.1
Instructor Heat Flux—Vertical (kW/m ²)				
OSB Extra Vent	2.2	1.4	4.3	3.1
OSB/Excelsior	2.0	0.6	4.3	1.2
Pallets/Excelsior	0.6	0.2	1.6	0.4
Straw	0.1	<0.1	0.2	0.2
Excelsior	0.1	<0.1	0.1	0.1

49°C) were lower than those from the Fire Behavior Lab rear instructor location (medians 60°C to 72°C). Similarly, heat fluxes at the first-floor instructor location (medians 1.7 kW/m² to 2.5 kW/m²) were lower than those from the Fire Behavior Lab front instructor location (medians 5.1 kW/m² to 8.4 kW/m²), and second-floor instructor location heat fluxes (medians 0.4 kW/m² to 0.6 kW/m²) were lower than those from the Fire Behavior Lab rear instructor location (medians 1.4 kW/m² to 2.1 kW/m²). Median and peak air temperatures and heat flux values were classified as *Ordinary* operating conditions (72°C to 200°C and 2 kW/m² to 12 kW/m²) on the first floor and *Routine* operating conditions (20°C to 72°C and < 2 kW/m²) on the second floor according to Utech's classification scheme as modi-

Table 8
Summary of Polycyclic Aromatic Hydrocarbon (PAH) Results from the First- and Second-Floor Instructor Location During the Exploratory Experiments

	First Floor	Second Floor
Σ PAH (mg/m ³)		
OSB Extra Vent	0.10*	0.09*
OSB/Excelsior	0.71	1.2
Pallets/Excelsior	1.9	1.3
Straw	0.75	2.4
Excelsior	0.18	0.92
Σ PAH _{carc} / Σ PAH		
OSB Extra Vent	NC*	NC*
OSB/Excelsior	80.4%	78.9%
Pallets/Excelsior	76.1%	74.4%
Straw	60.9%	61.2%
Excelsior	67.9%	65.6%
BaP _{TEQ}		
OSB Extra Vent	NC*	NC*
OSB/Excelsior	0.028	0.030
Pallets/Excelsior	0.050	0.034
Straw	0.040	0.063
Excelsior	0.029	0.037
BaP _{MEQ}		
OSB Extra Vent	NC*	NC*
OSB/Excelsior	0.010	0.011
Pallets/Excelsior	0.020	0.019
Straw	0.024	0.048
Excelsior	0.010	0.019

Σ PAH total concentration of PAHs

Σ PAH_{carc}/ Σ PAH percentage of total PAHs that were known, probable or possible carcinogens based on IARC classification of Group 1, 2A or 2B

BaP_{TEQ} toxic equivalent based on benzo(a)pyrene-relative toxicity equivalence factors

BaP_{MEQ} mutagenic equivalent based on benzo(a)pyrene-relative minimum mutagenic concentrations

*Only naphthalene and phenanthrene were detected

'NC' not calculated due to low PAH detection rates

For compounds that were not detected in concentrations above the limit of quantitation, the value of the reporting limit divided by square root of 2 was used in these calculations (see Table S.2)

fied by Madrzykowski [59, 60]. In contrast, heat fluxes at the front instructor location in the Fire Behavior Lab regularly reached *Emergency* conditions ($> 12 \text{ kW/m}^2$) in the timeframe necessary to complete training objectives. The average time instructors would need to work in these conditions in order to complete six ventilation cycles of fire dynamics training ranged from 25 s (Palletspallets) to 153 s (OSB) due to the higher heat fluxes produced by the OSB fuel packages in this structure [44].

Mean air temperatures were much lower at the instructor locations for the *OSB* fuel package with extra ventilation (due in part to the open door on the second floor), *Pallet* fuel package with excelsior (due to minimal involvement of pallets),

Table 9
Summary Benzene, Toluene, Formaldehyde, Acetaldehyde, Acrolein, 1, 3-Butadiene, Hydrochloric Acid, and Methyl Isocyanate Concentrations from the First- and Second-Floor Instructor Location During the Exploratory Experiments

	First Floor	Second Floor
Benzene (mg/m ³)		
OSB Extra Vent	0.4	<0.3
OSB/Excelsior	12	8
Pallets/Excelsior	11	11
Straw	3.3	17
Excelsior	1.1	5.3
Toluene (mg/m ³)		
OSB Extra Vent	<0.58	<0.60
OSB/Excelsior	<0.56	<0.62
Pallets/Excelsior	0.88	0.83
Straw	0.78	4.8
Excelsior	<0.61	1.3
1, 3 Butadiene (mg/m ³)		
OSB Extra Vent	<0.24	<0.25
OSB/Excelsior	<0.24	<0.24
Pallets/Excelsior	1.4	1.7
Straw	1.9	12
Excelsior	0.50	3.9
Formaldehyde (mg/m ³)		
OSB Extra Vent	1.1	<0.6
OSB/Excelsior	3.3	2.6
Pallets/Excelsior	7.0	7.5
Straw	1.9	13
Excelsior	1.3	11
Acetaldehyde (mg/m ³)		
OSB Extra Vent	<1.1	<1.2
OSB/Excelsior	4.2	5.1
Pallets/Excelsior	6.0	6.1
Straw	4.2	34
Excelsior	1.6	14
Acrolein (mg/m ³)		
OSB Extra Vent	<1.1	<1.2
OSB/Excelsior	1.2	<1.2
Pallets/Excelsior	2.0	2.4
Straw	<1.2	7.6
Excelsior	<1.2	4.3
Hydrochloric Acid (mg/m ³)		
OSB Extra Vent	5.0	2.4
OSB/Excelsior	<1.4	<1.5
Pallets/Excelsior	<1.5	<1.5
Straw	<1.6	2.9
Excelsior	<1.6	<1.6

Table 9
continued

	First Floor	Second Floor
Methyl Isocyanate (g/m ³)		
OSB Extra Vent	<1.8	<1.9
OSB/Excelsior	2.2	<1.8
Pallets/Excelsior	<1.8	<1.7
Straw	6.0	34.0
Excelsior	<1.8	4.0

Results shown with the less than symbol (<) are below the reporting limit (RL) and the value provided is RL divided by volume of gas collected

and smoke barrel experiments (approximately ambient temperature). Mean heat fluxes at the second-floor instructor location for the smoke barrels and *Pallet* fuel package with excelsior experiments were similar to the background measurements collected prior to ignition. On the other hand, second-floor instructor location heat fluxes for the *OSB* fuel package with extra ventilation experiment were the highest of any scenario tested, nearly double the next highest measurement recorded. This result was likely indicative of higher convective heat flux due to higher temperature gases and higher gas flow velocity in the flow path created by the additional ventilation openings. This experiment was the only one conducted where heat flux values at the second-floor instructor location would be classified as the higher risk (*Ordinary*; 2 kW/m² to 12 kW/m²) operating condition for any amount of time (peak values of 3.1 kW/m² to 3.4 kW/m²).

Many factors contribute to the differences in thermal conditions between these two training structures (single compartment Fire Behavior Lab vs. multi-compartment) even though the same materials were used in the fuel packages for replicate experiments. The total weight of fuels was different, and the ratio of pallets to sheet goods (OSB, fiberboard) in the multicompartment experiments described here was different than in the Fire Behavior Lab. The orientation of the fuel can impact combustion efficiency and evolved thermal conditions. The total volume (Fire Behavior Lab: 51.3 m³ vs. multicompartment: 347.5m³) of the structure can impact initial dilution and subsequent mixing of the combustion gases with ambient air. The materials used in construction (Fire Behavior Lab: steel vs. multicompartment: concrete) can impact the heat loss to the environment. Finally, structure ventilation can impact thermal conditions as shown in the *OSB* fuel package with extra ventilation scenario. However, ventilation is often decided based on training objectives, and in the case of the Fire Behavior Lab, the cycling of ventilation is required to achieve training objectives.

4.2. Airborne Chemical Compounds

Concentrations of airborne chemical compounds were approximately an order of magnitude lower than those reported using identical sampling methods in the Fire Behavior Lab [41], with the notable exception of HCl. Median total PAH concen-

trations ranged from 0.6 mg/m³ to 3.0 mg/m³ in this study, compared to 6.0 mg/m³ to 33.7 mg/m³ in [41] (Fig. S5 in Supplemental Materials). The live-fire experiments conducted in this study were similar in duration to the 3-cycle experiments with the Fire Behavior Lab, but 10 min to 20 min shorter than the median times of the 6-cycle Fire Behavior Lab experiments, particularly for the pallet fuel packages [41]. In the Fire Behavior Lab experiments, the pallet scenarios resulted in median total PAH concentrations that were much higher than fiberboard or OSB scenarios (14.4 mg/m³ vs. 7.8 mg/m³ and 9.1 mg/m³, respectively). However, when the fuel load was placed on a metal burn rack slightly elevated above the ground with increased access to oxygen, the *Pallet* fuel package resulted in significantly lower median total PAH concentrations compared to the *Fiberboard* and *OSB* fuel packages in this study (0.6 mg/m³ to 0.7 mg/m³ vs. 1.6 mg/m³ to 1.8 mg/m³ and 1.9 mg/m³ to 3.0 mg/m³, respectively). In related studies, Fent et al. measured total PAH personal gas concentrations (sampled by personal samplers located at chest height) with medians ranging from 2.78 mg/m³ for fire instructors conducting pallet and straw fuels scenarios in a concrete training structure to 34.0 mg/m³ for firefighters in an OSB, pallet, and straw-fueled scenario in a metal container-based structure [37]. Personal gas samples collected using similar methods from firefighters responding to controlled residential fires measured a median of 23.8 mg/m³ total PAHs (range 7.46 mg/m³ to 78.2 mg/m³) and 17.8 mg/m³ total PAHs (range 9.77 mg/m³ to 43.8 mg/m³) for firefighters assigned to attack and search job assignments, respectively [16]. Other studies have reported total PAH concentrations of 0.43 mg/m³ to 2.70 mg/m³ for particle board-fueled training fires in Australia [31], 75 mg/m³ to 180 mg/m³ for particle board-fueled training fires also in Australia [35], and 19 mg/m³ to 41 mg/m³ (sum of 22 PAHs) for chipboard-fueled training fires in Sweden [34].

Similar to previous reports from training fire research, benzene was the most abundant BTEXS compound measured. Area gas concentrations of benzene measured at the 0.9 m working height inside the structure (median range of 2.5 mg/m³ to 28 mg/m³) were 10 to 100 times lower than that measured in the Fire Behavior Lab (median range of 19 mg/m³ to 270 mg/m³, Fig. S6 in Supplemental Materials) [41], but similar to the personal gas concentrations measured by Fent et al. where the median range was 9.6 mg/m³ to 29 mg/m³ for instructors during live-fire exercises involving different fuels and structures [37]. Kirk and Logan reported comparable gas concentrations of benzene during compartment fire behavior training sessions using particle board (4.5 mg/m³ to > 7.8 mg/m³) [39]. On the other hand, Laitinen et al. reported area gas concentrations of benzene ranging from 0.62 mg/m³ for pure spruce and pine wood-fueled fires to 1.0 mg/m³ for chipboard-fueled fires (which also included polyurethane foam and kerosene) to 2.5 mg/m³ for conifer plywood-fueled fires [29]. In comparison, Fent et al. measured much higher personal gas concentrations of benzene from firefighters who were assigned to search and attack firefighting tasks inside controlled residential fires (median 121 mg/m³ and 129 mg/m³, respectively with peak concentrations near 1000 mg/m³ for both groups) [16].

In the Fire Behavior Lab experiments, the impact of fuel package on benzene concentrations was dependent on the different sampling locations inside the struc-

ture (front or rear instructor location) [41]. The OSB fuel package experiments resulted in median benzene concentrations that were higher than the fiberboard or pallet scenarios at the rear instructor location (220 mg/m^3 vs. 72 mg/m^3 and 100 mg/m^3 , respectively). On the other hand, OSB and pallet fuel packages resulted in similar median concentrations at the front instructor location (89 mg/m^3 and 98 mg/m^3 , respectively) [41]. In that study, it was noted that the fuel packages had differing impacts on the fire dynamics environment, which can impact the distribution of smoke within the structure. When fiberboard and OSB fuel packages were compared in shorter duration experiments where similar fire dynamic environments were created, there were no notable differences in airborne benzene concentrations. In the current study, when the fuel package was on a metal rack slightly elevated above the ground with increased access to oxygen, the *Pallet* fuel package consistently resulted in the lowest median benzene concentrations compared to *Fiberboard* and *OSB* fuel packages (2.5 mg/m^3 to 3.2 mg/m^3 vs. 13 mg/m^3 to 17 mg/m^3 and 28 mg/m^3 , respectively).

Median 1, 3 butadiene concentrations in the multicompartment structure were typically two orders of magnitude lower than in the Fire Behavior Lab for the same training fuels (multicompartment: 0.27 mg/m^3 to 0.44 mg/m^3 , Fire Behavior Lab: 15 mg/m^3 to 65 mg/m^3 at the rear instructor location). However, the three highest overall airborne concentrations of 1, 3 butadiene were measured in the smoke barrel experiments with straw (1.9 mg/m^3 and 12 mg/m^3) and excelsior (3.9 mg/m^3). The *Pallet* fuel package with excelsior experiment also stands out in its relatively high concentrations of 1, 3-butadiene (1.4 mg/m^3 and 1.7 mg/m^3 at the first and second floor respectively) relative to the distributions from with *Pallet* experiments. The common factor in each of these experiments is that smoldering combustion was a relatively larger contributor to smoke production compared to flaming combustion in the others.

Formaldehyde was present in high concentrations relative to its occupational exposure limits as has been reported in several other studies. Also, similar to previous studies, the relative differences between median concentrations produced by the different fuel packages (*Pallet*: 3.7 mg/m^3 to 4.7 mg/m^3 , *Fiberboard*: 4.9 mg/m^3 , *OSB*: 4.6 mg/m^3 to 5.7 mg/m^3 , with considerable overlap in overall ranges) was not as large as with total PAHs or benzene. In the Fire Behavior Lab, the same three fuels studied here produced levels of formaldehyde at the rear instructor location at the 0.9 m height that were similar to each other (median range of 44 mg/m^3 to 48 mg/m^3), though nearly an order of magnitude larger than measured in this study (Fig. S7 in Supplemental Materials) [41]. Fent et al. also found comparable levels of formaldehyde between a pallet and straw scenario and one type (labeled as ‘Alpha’) of OSB (4.6 mg/m^3 vs. 4.5 mg/m^3), with similar magnitudes as reported here (also in similar sized structures) [37]. Laitinen et al. reported mean formaldehyde concentrations ranging from 0.3 mg/m^3 to 1.5 mg/m^3 for training fires involving wood-based fuels in a ‘fire house’, and 11 mg/m^3 for training fires in a ‘gas simulator’ [29]. Kirk and Logan reported similar gas concentrations of formaldehyde during compartment fire behavior training sessions (0.53 mg/m^3 to 5.0 mg/m^3) [39]. The median acrolein concentrations reported here were also similar across the different fuels (*Pallet*: 2.2 mg/m^3 to 3.0 mg/m^3 , *Fiber-*

board: 1.7 mg/m³ to 2.0 mg/m³, OSB: 2.7 mg/m³ to 2.8 mg/m³, with considerable overlap in overall ranges). These results are on the low end of those measured inside the Fire Behavior Lab structure (median range of 3.4 mg/m³ to 32 mg/m³) [41] or the levels measured during live-fire exercises in Fent et al. where the median range was 4.9 mg/m³ to 60.6 mg/m³ [37].

Airborne HCl in these training fire environments were similar across the different fuel packages (median concentrations for *Pallet*: 9.3 mg/m³ to 9.8 mg/m³, *Fiberboard*: 10 mg/m³ to 11 mg/m³, *OSB*: 12 mg/m³ to 13 mg/m³, with considerable overlap in overall ranges). These concentrations are notably higher than median values reported in the Fire Behavior Lab with the same fuel packages (non-detect to 2.8 mg/m³) [41], contrary to the other airborne compounds reported here. In Horn et al. and Fent et al., the pallet-fueled scenario resulted in the highest concentrations of HCl [37, 41]. The fuel packages used here and in Fent et al. utilized a larger proportion of pallets and straw in the OSB and fiberboard scenarios than in Horn et al., which may account for the higher relative concentrations in those studies. It is interesting to note that HCl was detected in all 16 experiments where pallets and straw were used (with or without fiberboard/OSB), but HCl was not detected at either sampling location in any of the three exploratory experiments where excelsior was substituted in place of the straw. Chlorine and other halogens occur in nature and may be absorbed by trees and/or straw. While these three independent studies have now shown higher concentrations with pallet and straw fuel packages, it is unknown whether this fuel package would contain more chlorine than timber used in the other wood-based products.

Considering all the fuels studied here, the highest concentrations of benzene and PAHs were measured during the *OSB* fuel package experiments. However, the peak concentrations of most of the other compounds were from a smoldering smoke barrel with straw. Compared to flaming combustion, smoldering fires have been shown to result in higher yields of many chemical compounds for the same mass of material consumed due to less efficient combustion, though often at lower mass consumption rates [61]. Although the fire service has been made aware of the concern in using engineered wood products in training fuel packages, anecdotally, they are often less concerned with the smoke produced by smoldering straw or excelsior in smoke barrels. The air temperature increase when using a smoke barrel is much lower than with a flaming wood-based fuel package, so some instructors have been traditionally less vigilant about using airway protection while inside or immediately outside training structures using these fuel packages. HCl is a respiratory irritant, which may encourage more stringent use of respiratory protection, but relatively low concentrations were detected in the straw smoke barrel compared to the flaming wood-based fuel packages [below OSHA PEL Ceiling limit (7 mg/m³)], and HCl was not detected for the excelsior smoke barrel experiment. These data should further reinforce the need for use of respirator protection when firefighters are working in and around smoke, and more research should be conducted with replicate experiments using smoldering fuel packages.

On the other hand, the lowest concentration of nearly all airborne compounds measured here were from the single experiment using OSB, pallets, and straw with

two important changes in ventilation. The open window on the first floor and doorway on the second floor increased ventilation to the fuel package and resulted in the highest ceiling temperatures in the fire room and heat flux at the second-floor instructor location of all 20 tests. However, this flow path also allowed much of the smoke to escape the second floor, resulting in the least impact on visibility and overall lowest concentration of contaminants at each instructor location.

Even though air temperatures were much lower on the second floor of the multi-compartment training structure, the airborne concentrations of nearly all compounds measured in this study were similar between the first-floor and second-floor instructor locations and in some cases higher on the second floor. Adding smoke barrels on the second floors may further increase airborne concentrations of these compounds at higher elevation, though with minimal impact on air temperature. The low air temperatures and distance from the radiant flame (or lack of flames in the smoke barrel sources) may lure some instructors into less consistent use of respiratory protection. Once again, these measurements reinforce the need to maintain respiratory protection even at these remote instructor locations.

By combining this data set with that from a Fire Behavior Lab using identical fuels, measurement techniques, and measurement height (simulating a crouching instructor's head location) [41], the ability for a fire instructor to impact airborne air concentrations through fuel package and structure ventilation practices can be further understood. It is apparent that the material selected for fuel packages in training fires can have an important impact on compounds in the air, particularly VOCs and PAHs. However, the orientation of those fuels and how they are incorporated into the fuel package also impact the relative contribution of contaminants in the air, particularly for the PAHs. Likewise, changing ventilation configurations had the most dramatic impact on concentrations of the measured airborne contaminants but also impacted the training fire environment created and thus, may not always be appropriate. Finally, the layout and volume of the training structure play an important role in the concentration of contaminants in the structure.

The smoke created with the intention of impacting visibility and/or fire dynamics in the training fire environment must be understood along with its contribution to airborne toxicants. Of the replicate fuel packages tested in this study, *OSB* had the largest impact on visibility followed by *Fiberboard*, then *Pallet*. The overall ranking of airborne chemical concentrations followed the same trend. The straw smoke barrel on the second floor likewise resulted in a dramatic reduction in visibility, much more so than on the first floor. The excelsior smoke barrels resulted in slightly less impact on visibility than the straw for both floors. Once again, decreasing visibility was associated with increasing concentration of airborne contaminants. Finally, the *OSB* fuel package with extra ventilation had the least impact on visibility and resulted in the lowest overall concentrations of airborne contaminants. The Fire Behavior Lab experiments (with noted differences in fuel package load, structure geometry, and ventilation) resulted in darker smoke with sufficiently high concentrations of unburned hydrocarbons to ignite and create rollover and/or flashover. Those experiments resulted in concentrations of contaminants that were often 10 to 100 times higher than those measured in this

study. The Fire Behavior Lab study also showed that when less smoke was created (resulting in only surface burning in the fire area), the concentrations of contaminants in the smoke were much lower than when sufficient smoke was created to support rollover/flashover. These results further our understanding of the relationship between visibility in fires and concentrations of airborne chemicals in the smoke. Similarly, Purser has shown carbon monoxide and hydrogen cyanide concentrations increase with decreasing visibility and the concentrations of CO are higher for under-ventilated fires than well-ventilated fires for the same visibility [62].

4.3. Limitations and Future Work

There are important limitations to this work. Throughout the study, weather and ambient conditions varied between warm and sunny to cold and rainy, which likely contributed to variability in results. For some compounds, this variability was greater within a fuel package than between fuel packages. The fuels selected in this work are commonly used in the fire service today in the United States and around the world, but there are other materials (e.g. medium density fiberboard, soy based plywood, etc.) that can be used for training fires and should be studied.

Future research should expand to study the biological uptake of chemicals by firefighters and instructors when working in these training fire environments. Such research should consider the holistic impact of implementing contamination control measures on chemical and thermal exposure as well as learning objectives. Additional study regarding the risk from fuel packages that are intended to smolder, such as smoke barrels with straw or excelsior, is required. These exploratory experiments provide an important opportunity to compare a single test to a distribution of data from the other fuel packages, but multiple replicates of measurements from these environments are needed to draw stronger conclusions.

4.4. Conclusions

When training fire environments were created with three different fuel packages on the first floor of a multi-compartment training structure, first-floor temperatures and heat fluxes at the instructor locations were considerably higher than those from the second floor due to the proximity to the fire room. While the *Pallet* fuel package consistently resulted in the lower median time-averaged temperatures and heat fluxes compared to the *OSB* and *Fiberboard* fuel packages, there was no significant differences outside of the fire room at either simulated instructor location.

Fuel packages that included *OSB* and *Fiberboard* produced the highest median concentrations of total PAHs and VOCs (e.g. benzene) measured in this study, while the *Pallet* fuel package produced the lowest median concentrations of these compounds. These trends generally followed the qualitative visual obscuration created by each fuel. Airborne concentrations of compounds measured in this study at both the first and second floor instructor locations were similar, which reinforces the need to maintain respiratory protection throughout the entire training structure.

Exploratory tests were conducted to investigate the impact of increased ventilation and the use of smoldering smoke barrels. The training fire environment created by the *OSB* fuel package with increased ventilation resulted in the highest fire room temperatures but the lowest impact on visibility throughout the structure. Further, this test resulted in the lowest overall concentrations of contaminants in this study. In contrast, the smoldering straw-filled smoke barrel had minimal impact on the thermal environment but created a highly obscured environment and some of the highest concentrations of the targeted contaminants of any test.

It should be highlighted that decreasing visibility was associated with increasing concentration of airborne contaminants in this study. The data clearly demonstrates the need for consistent use of respiratory protection when firefighters are working in and around smoke and the need for post fire PPE cleaning and skin hygiene regardless of the fuel package. These data may be useful in balancing obscuration for training with potential exposure to thermal stressors and contaminants.

The fire service should understand the risk–benefit tradeoff when creating an elevated thermal environment for training. Trainees benefit from working in these hot environments for acclimatization, familiarization, sensing, and reacting to the environment as well as understanding PPE and firefighting tool operations, capabilities, and limitations. However, this benefit is balanced with increasing the risk for skin burns and PPE damage. The fire service and fire training organizations should take a similar approach to balancing the benefit of creating an environment where fire instructors and trainees work in reduced visibility and/or ignitable smoke with the increased risk for exposure to contaminants through dermal absorption, inhalation (when airway protection is not properly worn), and contaminated PPE.

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Data Availability

Data can be made available upon request.

Declarations

Conflict of interest 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.

Ethical Approval Not applicable.

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SUPPLEMENTARY INFORMATION

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