Exposure Risks and Potential Control Measures for a Fire Behavior Lab Training Structure: Part B—Chemical Gas Concentrations

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Abstract. Firefighters' or instructors' exposure to airborne chemicals during live-fire training may depend on fuels being burned, fuel orientation and participants' location within the structure. This study was designed to evaluate the impact of different control measures on exposure risk to combustion byproducts during fire dynamics training where fuel packages are mounted at or near the ceiling. These measures included substitution of training fuels (low density wood fiberboard, oriented strand board (OSB), pallets, particle board, plywood) and adoption of engineering controls such as changing the location of the instructor and students using the structure. Experiments were conducted for two different training durations: the typical six ventilation cycle (six-cycle) and a shorter three ventilation cycle (three-cycle) with a subset of training fuels. In Part A of this series, we characterized the fire dynamics within the structure, including the ability of each fuel to provide an environment that achieves the training objectives. Here, in Part B, airborne chemical concentrations are reported at the location where fire instructors would typically be operating. We hypothesized that utilizing a training fuel package with solid wood pallets would result in lower concentrations of airborne contaminants at the rear instructor location than wood-based sheet products containing additional resins and/or waxes. In the six-cycle experiments (at the rear instructor location), OSB-fueled fires produced the highest median concentrations of benzene and 1,3 butadiene, plywood-fueled fires produced the highest total polycyclic aromatic hydrocarbon (PAH) concentrations, particle board-fueled fires produced the highest methyl isocyanate concentrations, and pallet-fueled fires produced the highest hydrogen chloride concentrations. All fuels

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other than particle board produced similarly high levels of formaldehyde at the rear instructor location. The OSB fuel package created the most consistent fire dynamics over six-cycles, while fiberboard resulted in consistent fire dynamics only for the first three cycles. In the follow-on three-cycle experiment, PAH, benzene, and aldehyde concentrations were similar for the OSB and fiberboard-fueled fires. Air sampling did not identify any clear differences between training fires from burning solid wood pallets and those that incorporate wood-based sheet products *for this commonly employed fuel arrangement with fuels mounted high in the compartment*. However, it was found that exposure can be reduced by moving firefighters and instructors lower in the compartment and/or by moving the instructor in charge of ventilation from the rear of the structure (where highest concentrations were consistently measured) to an outside position.

1. Introduction

There is sufficient evidence that the occupation of firefighting can lead to long-term health risks including cancer [1] based on a number of epidemiology studies that have identified an elevated risk of cancer in the fire service compared to non-firefighter controls (e.g., [2–12]). One of the most studied aspects of firefighters' occupational risk for cancer is potential exposure to products of combustion. Firefighters may be exposed to numerous chemical compounds produced by burning materials during emergency responses and training fires, including polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) such as aromatic hydrocarbons and aldehydes, particulates and other products of incomplete combustion (e.g., [13–21]). Importantly, elevated biological levels of PAHs and VOCs have been found in firefighters after firefighting activities [21–26]. Firefighters' exposure to these compounds may occur through inhalation when respiratory protection (particularly a self-contained breathing apparatus (SCBA)) is not worn such as when operating outside of a structure or when dislodged or temporarily removed. Turnout gear could off-gas VOCs and some PAHs after SCBA has been removed, further contributing to firefighters' inhalation exposure [27–29]. It has been shown that turnout gear provides little attenuation against the ingress of certain vapors [30–32] and that some of these compounds (e.g., pyrene, phenanthrene, naphthalene, benzene) can be absorbed dermally [25, 26, 33]. Dermal absorption, in addition to inhalation, likely contributes to exposure risk for firefighters on the fireground and training ground.

Many firefighters routinely conduct live-fire training to maintain and build proficiencies and certifications. Active firefighters often serve as instructors, where they may experience multiple instructional fires per day over a combined period of several weeks or even months. Thus, training fires may constitute a major portion of some firefighters' occupational exposures to products of combustion. Glass et al. found a dose–response relationship between estimated exposures from training fires and cancer incidence at a fire training college in Australia [6]. The high exposure group at the fire training college had increased risk of all cancers (com-

bined), as well as testicular cancer and melanoma, compared to the general population. Fent et al. found that a single day of live-fire training scenarios (three training fires) resulted in an increase of 1-hydroxypyrene in urine (metabolite of pyrene) for instructors that was 0.8- to 3.5-times the median levels measured from firefighters after a controlled residential fire response [25, 26]. The environment created to achieve learning objectives (fuel, ventilation, and structure) for these training fires appeared to be important factors for the biological levels of PAH metabolites.

While conducting training fires, the fire service may be able to select specific training fuel packages (i.e., employ a substitution control measure) to help manage health and safety concerns. Of course, the choice of training environment will be dictated largely on training objectives, but it is also prudent to balance what will be gained from training with the risks it poses. Unfortunately, the fire service is currently lacking evidence-based guidance on the impact of substituting one training fuel for another related to chemical and thermal exposures, or the extent to which learning goals can be affected by such substitutions. *National Fire Protection Association (NFPA) 1403: Standard on Live Fire Training Evolutions* outlines the minimum requirements for conducting live fire training and includes guidance for conducting such training so that learning objectives are achieved with the goal of mitigating health and safety hazards [34]. In Section 4.13, NFPA 1403 requires that fuel materials be only wood products, defining acceptable fuels (in the appendix) as "…pine excelsior, wooden pallets, straw, hay, and other wood-based products…" [34], but the category of 'other wood-based products' may include a range of materials that could have different burning characteristics. Currently, there are no materials specifically designed for live-fire training, so the fire service will typically incorporate commonly available combustibles. Firefighters' exposures during live-fire training exercises have been studied in research projects that used solid wood, particle board/chipboard, plywood, oriented strand board (OSB), diesel fuel, and heating oil as fuel sources [20, 21, 26, 35–47]. Of these, only two studies directly compared exposure of firefighters working in different training fire environments, and in both studies, the training environments differed with respect to fuels used and the training structure [26, 39–41].

Laitinen et al. compared firefighter exposures from training in a gas-fired simulator to exposures in a 'conventional simulator' using different fuels: chipboard (with polyurethane foam and kerosene firing liquid), plywood (with sinol firing liquid), or spruce wood (with sinol) [39, 40]. Exposure to pyrene was assessed through metabolites in the urine and was found to be highest in the plywood scenario followed by chipboard, solid wood, then gas simulator scenarios. On the other hand, the highest airborne concentration of formaldehyde was measured in the gas-fired simulator. Although overall exposures were typically lower with the gas simulator, the authors provide the following important caveat, "*The test situation was artificial and the smoke behaved in a totally different way than it would in a real fire*" [40].

Fent et al. created live fire training environments using either pallet and straw fuels in a traditional concrete training structure or OSB (in addition to pallet and straw) in a metal container-based training structure [26, 41]. Maximum concentrations of many of the measured compounds were above applicable short-term occupational exposure limits during the fire period of both the pallet and straw and OSB scenarios. Furthermore, even though firefighters and instructors donned full PPE including SCBA prior to entering the structure and doffed after suppression (upwind of the structures), exhaled-breath concentrations and urinary biomarkers confirmed systemic exposures to PAHs and VOCs. Participants who worked in the highest average air concentrations or duration of exposure also had the highest urinary metabolites in the hours after exposure. It is important to note that this study did not isolate the impact of any one parameter that may impact exposure risk (e.g., training fuel, training structure, firefighting/training operations). However, these studies do provide insight into potential administrative and engineering control measures that may assist in exposure risk reduction.

In Part A of this series, we characterized the fire dynamics within a common training structure using five different commonly available training fuels, with a focus on understanding thermal risks and the ability of each fuel to provide an environment that achieves the training objectives [48]. The purpose of this (Part B) paper is to characterize the potential airborne chemical exposures to known, probable, and possible carcinogens for a fire instructor operating in this training structure using the same training fuels, with an additional focus on how these exposure risks are impacted by controllable factors (i.e., fuel substitutions, instructor locations, relative height of measurements).

2. Methods

Live-fire training experiments were conducted at the Delaware County Emergency Services Training Center (ESTC) in Sharon Hill, Pennsylvania. Fire dynamics training scenarios were conducted in a common training structure commonly referred to as a flashover simulator and specifically called out in NFPA 1402 and 1403, as a Fire Behavior Lab [34, 49] (Figure 1). A variety of training objectives can be met by using a Fire Behavior Lab. Examples include the observation of fire development, fire rollover, and the impact of changes to the ventilation. The core feature of the training structure is the ability to generate ventilation limited fire conditions which can be controlled to create flame spread across the hot gas layer accumulating below the ceiling of the structure, also known as a rollover condition and eventually floor-to-ceiling flaming in the fire area providing an indication of flashover. A common training evolution in the Fire Behavior Lab would include up to six different ventilation cycles (six-cycle) where fire dynamics would be demonstrated after opening and closing structure vents six times (though some training organizations will conduct as few as three ventilation cycles (three-cycle)). In order to teach and demonstrate fire dynamics behavior, each ventilation cycle should generate a rollover and/or flashover. If a rollover or flashover was
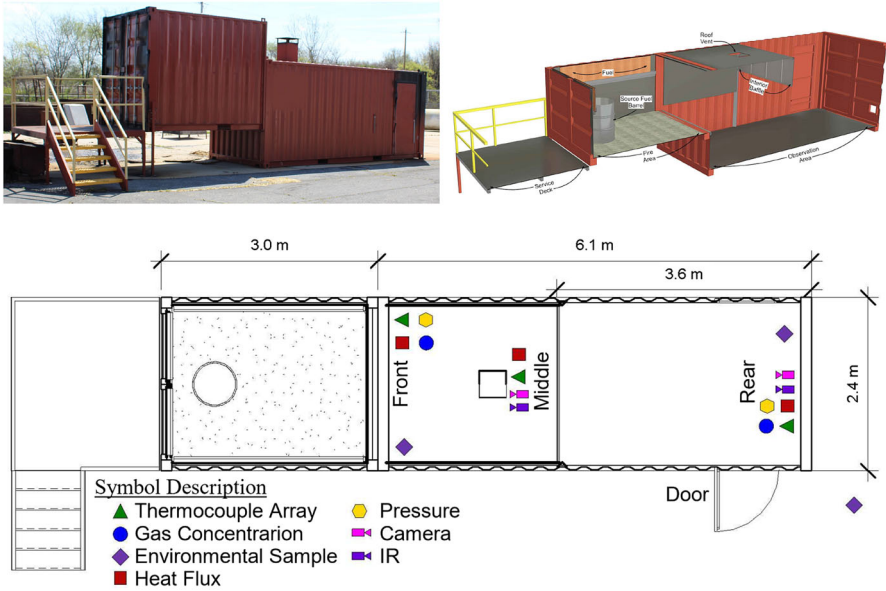
Figure 1. Fire behavior lab structural layout and sampling locations.

not generated during a ventilation cycle then the training objective could not be met.

Prior to data collection, 13 pilot experiments were conducted to evaluate the fire dynamics characteristics of each different fuel and iterate gas sampling strategies (e.g., flow rates, filtering arrangements, thermal protection) to reduce the risk for pump failures and sample clogging. During the pilot experiments an instructor trained in the operation of this structure observed fire conditions from a command station with visible and infrared cameras. Based on this information that instructor was able to coordinate ventilation for the remaining experiments from outside of the structure.

2.1. Study Design

This study was designed to characterize the gas concentrations produced by utilizing five different wood-based products commercially available in eastern Pennsylvania (USA) in a Fire Behavior Lab. Five different fuels (fiberboard, OSB, pallets, particle board, and plywood) were utilized for the six-cycle experiments following instructional guidelines provided by the training structure manufacturer. The order of introduction followed a block randomization scheme with five experiments per block (i.e., each of the five fuels was used in the first five experiments, then reordered for the next five experiments, etc.) to reduce any bias from changing environmental conditions when using the outdoor training structure. Due to inconsistent fire dynamics near the end of the longer six-cycle experiments with

fiberboard and pallets, a follow up set of three-cycle experiments comparing only fiberboard and OSB were conducted, with the order varying over a 3 day test period.

At the beginning of each day of experiments, background pre-fire area gas samples were collected over 30 min in the observation area. Two minutes prior to ignition, sampling pumps (located inside insulated cabinets) were turned on and sampling media (with inlet extending just outside the insulated cabinet) were simultaneously exposed at locations that represent instructors located at the front and rear of the fire behavior lab. A third set of sampling pumps and media were turned on within 30 s of those in the observation area and placed at a location outside of the structure where instructors would be located. While each experiment had the same training objective (demonstrate fire dynamics for six or three ventilation cycles), the time to complete the training scenario depended on the burning rate of each fuel which was influenced by fuel type, moisture content, and ambient conditions (e.g., humidity, wind) [48]. After the fire training scenario was complete, staff members entered the training structure to remove the insulated cabinets that contained the sampling pumps. Sampling pumps were turned off, sampling media were capped and stop time was recorded (typically less than 2 min after completion of the last ventilation cycle). Similar activity was conducted on the outside instructor sampling location pumps. The timing of when the media was exposed and capped was recorded for each location. Two or three separate experiments were conducted each day with a minimum of 2 h between each.

2.2. Test Structure and Fuel Load

The Fire Behavior Lab (Figure 1) and fuel load was described in detail in Part A of this series [48]. To summarize, the training structure was constructed by connecting two portions of 2.4 m wide square cross section steel shipping containers. The observation area was approximately 6.1 m long and the fire area 3.0 long and offset by 0.9 m vertically from bottom of the observation area. In the observation area, a single 2.0 m tall × 0.9 m wide rear door and a 0.38 m square roof vent were used for venting during experiments. The observation area container was equipped with an interior baffle that extended across the entire width of the structure, 0.7 m below the ceiling, and was left closed for all experiments. In the fire area, the fuel load was mounted on the ceiling as well as along the upper 1.2 m of the walls and rear doors. A fuel source barrel was centered in the 2.4 m wide fire area and off set 0.3 m from the fire area doors. Training fuel preparation was carefully controlled for each experiment, with all materials used for the five replicates of each fuel package being sourced from the same manufacture and distributor and fuels packages loaded into the training structure in a consistent manner.

2.3. Training Protocol

Prior to ignition, the rear door was propped open and the roof vent was closed. The pallets and straw in the fuel source barrel were ignited with a propane torch. In all cases, fire spread from the source barrel to the fuels on the walls and ceiling. The first fire development bench mark was met when smoke filled the upper

portion of the fire area down to the middle of the source barrel. The timing for the training fire environment to develop to this point varied between each scenario based on fuel and environmental conditions. The fire development and ventilation cycle times were recorded and are reported in [48]. Once these conditions were met, the roof vent was fully opened. The smoke lifted, and the fires transitioned to a steady state with flame rollover into the observation area and the goal to reach simulated flashover conditions (where flames reached the baffle and were approximately 0.3 m from the floor of the fire area). In some scenarios, a rollover condition was not reached and the first cycle was terminated once steady burning conditions were determined through visual observations and thermal measurements. After flashover (or steady state) conditions were reached (median time ranged from 532 s for OSB to 933 s for pallets [48]), the roof vent and rear doors were closed. Vents remained closed until the smoke layer in the fire area descended to the point where the fuel source barrel was no longer visible or (later in the training scenario) conditions reached a steady state. All following cycles were vented in an identical manner, with two instructors outside of the structure simultaneously activating the door to the observation area and the vertical vent fully opened. Smoke lifted and the fire returned to flashover or rollover conditions or steady state burning. Closing of the ventilation openings marked the completion of a single ventilation cycle.

At completion of the experiments (i.e., after either six or three ventilation cycles), the fire area was washed out with water from a hoseline and any remaining materials in the structure were 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.

Table 1
Area Gas Sample Collection and Analysis Methods

Compound	Sampling media	Flow rate (L/min)[a]	Analytical method
1,3-Butadiene	SKC 226–09 Charcoal tube 600 mg	0.05/0.25	NIOSH 1024
Acid gases (HCl, HF)	Silica gel 400/200 mg with glass fiber filter plug	0.20	NIOSH 7903
Aldehydes (Formaldehyde; Acetaldehyde, Acrolein)	SKC 226–117 Treat XAD for Ald-GC	0.03/0.10	OSHA 52-GCNPD; OSHA 52/OSHA 68 mod
Isocyanates	Asset EZ4-NCO	0.50	ISO 17734
Phthalates	OVS-Tenax w/GFF	1.0	OSHA 104
Polycyclic Aromatic Hydrocarbons (PAHs)	SKC 226–57, XAD-7/Glass Fiber Filter (OVS) 100/200 mg	1.0	NIOSH 5528
Benzene, Ethyl benzene, Toluene, Xylenes, Styrene (BTEXS)	SKC 226–01 Charcoal tube 150 mg	0.05/0.20	NIOSH 1501

[a]Flow rates for some compounds (1,3-Butadiene, Aldehydes, and BTEXS) were reduced for samples collected inside the training structure after pilot testing to reduce risk for breakthrough and/or clogging

2.4. *Area Gas Sampling*

The area gas sampling strategy was selected to extend the work of Fent et al. [41], which provides the most complete characterizations of compounds measured during live fire training in the literature to date. Table 1 provides a summary of the area gas sample collection including sampling media, flow rates, and analysis methods utilized to characterize 1,3-butadiene, acid gases, aldehydes, isocyanates, phthalates, PAHs, and aromatic hydrocarbon VOCs. The VOC sampling method focused on quantifying benzene, toluene, ethyl benzene, xylenes, and styrene (BTEXS). The aldehyde sampling methods were concentrated on formaldehyde, acetaldehyde, and acrolein. Based on the series of pilot tests with each training fuel, low levels of many of the analyzed isocyanates, phthalates, and acid gases were detected. Detection rates for methylene diphenyl diisocyanate (MDI), bis(2-ethylhexyl)phthalate, dibutyl phthalate, diethyl phthalate, di-n-octyl phthalate, and hydrofluoric acid (HF) collected during the first 10 experiments were low, thus sampling was terminated for these analytes and the data will not be reported. The production and transport of many of these compounds can depend on temperature and humidity, and some of these gases may be lost from the air through condensation onto metal surfaces. It is possible that these compounds could be detected in other training fire scenarios conducted in different ambient conditions and/or with concrete or drywall lined structures.

For the six-cycle experiments, sampling media were located at the front and rear instructor locations, roughly 0.9 m above the floor to approximate head height of a sitting or crouching instructor (Figure 1). At the outside location, sampling pump intakes were located 1.5 m above the ground in the approximate breathing zone for a standing instructor. In the three-cycle experiments, samples were collected at heights of 0.3, 0.6, and 0.9 m above the floor to study vertical distribution of compounds at the rear instructor location. 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 1. All media were stored pre and post sampling (per analytical method described in Table 1), in either a refrigerator and/or freezer and shipped on ice to the analytical laboratory under chain of custody.

While there exist hundreds of known PAHs, the US Environmental Protection Agency (EPA) has designated sixteen as High Priority Pollutants because of their potential toxicity as well as their prevalence and persistence in the environment [50]. 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 ($\sum$ PAH),

$$\sum PAH = [Ace] + [Acy] + [An] + [BaA] + [BaP] + [BbF] + [BghiP] \\ + [BkF] + [Ch] + [DBA] + [Fl] + [Fla] + [IP] + [Nap] + [Ph] + [Py] \tag{1}$$

(B) percentage of total PAH that were carcinogenic based on IARC classification of Group 1, 2a, or 2b ($\sum$ PAH$_{\text{carc}}$/$\sum$ PAH),

$$\sum PAH_{carc} \Big/ \sum PAH = \left(\left(\begin{array}{c} [BaA] + [BaP] + [BbF] + [BkF] \\ + [Ch] + [DBA] + [IP] + [Nap] \end{array} \right) \Big/ \sum PAH \right) \\ * 100 \tag{2}$$

(C) Benzo[a]pyrene-relative toxicity equivalence (BaP_TEQ),

$$BaP\_TEQ = 0.001 * ([Ace] + [Acy] + [Fla] + [Fl] + [Nap] + [Ph] + [Py]) \\ 0.01 * ([An] + [Ch] + [BghiP]) + 0.1 * ([BaA] + [BbF] + [BkF] + [IP]) \\ + 1 * [BaP] + 5 * [DBA] \tag{3}$$

(D) Benzo[a]pyrene-relative mutagenic equivalence (BaP_MEQ),

$$BaP\_MEQ = 0.00056 * [Acy] + 0.082 * [BaA] + 1 * [BaP] + 0.25 * [BbF] \\ + 0.19 * [BghiP] + 0.11 * [BkF] + 0.017 * [Ch] \\ + 0.29[DBA] + 0.31[IP] \tag{4}$$

The values of weighting parameters used in Eqs. 3 and 4 were presented in Nisbet and LaGoy and Durant et al. [51, 52]. 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 [53]. Due to sample size and variability, tests of significance were not conducted across fuel types.

3. Results

Background samples collected in the morning of each training fire day ($N = 13$) resulted in detectable levels only for acenaphthylene (0.0042 mg/m^3 to 0.0066 mg/m^3 on Days 2, 3, 4, 12 and 13), ethylbenzene (0.32 mg/m^3 on Day 8), formaldehyde (0.34 mg/m^3 to 0.63 mg/m^3 on Days 2, 3, 4 and 13), naphthalene (0.0068 mg/m^3 to 0.015 mg/m^3 on Days 2, 3, 4, 7, 8, 10, 12 and 13) and phenanthrene (0.0032 mg/m^3 on Day 13). These background levels were typically two to three orders of magnitude below values measured during the live-fire experiments and showed no indication of increasing from the beginning to the end of the

Table 2
Training Fire Scenario Duration from Ignition of the Fuel Source Barrel to the Time When Sampling Cabinets Are Removed from the Fire Behavior Lab

	Sampling time (min:sec)		Qualitative fire dynamics (percentage of cycles)		
	Median	Range	Flashover (%)	Rollover (%)	Surface burning (%)
Six ventilation cycles ($N = 5$)					
Fiberboard	24:54	22:31–31:23	23	32	45
OSB	21:40	19:47–22:53	63	31	6
Pallets	31:12	27:08–41:05	30	42	27
Particle Board	23:46	23:26–24:31	61	33	6
Plywood	24:02	21:33–25:13	43	33	24
Three ventilation cycles ($N = 3$)					
Fiberboard	14:56	14:24–16:03			
OSB	16:42	14:38–16:52			

For the six ventilation cycle experiments, a summary of the qualitative fire dynamics generated for each training fuel is summarized from Ref. [48]

experiments, suggesting that there was no buildup of contaminants during the test series.

For the six-cycle experiments, there was a large range of burn times necessary to complete training objectives among different fuels as well as notable variations within each type of fuel (Table 2). Some of this variability was due to difficulty in achieving rollover, particularly later in the training scenario for fiberboard, pallet and plywood fuels as discussed in [48]. OSB-fueled scenarios were consistently completed in the shortest amount of time with relatively low variability. Pallet-fueled scenarios required the longest median time to complete, while also being the most variable. Table 2 includes a summary of the fire dynamics environments that were presented to students during each of the six cycle experiments as assessed by 11 members of the project team representing training organizations across the United States [48]. To achieve the training objectives, each ventilation cycle should produce sufficient fire growth to generate a rollover and/or flashover. Fiberboard-fueled experiments resulted in the lowest combined percentage of flashover and rollover fire dynamics demonstration, particularly after the first three cycles were complete. Therefore, a follow-on set of three-cycle experiments were conducted with OSB and fiberboard fuels in order to compare airborne chemical concentrations when similar fire dynamics are presented. The three-cycle experiments resulted in shorter times necessary to conduct the training with less variability. It is important to note that the concentrations in tables that follow were averaged over these sampling times (in order to allow direct comparison to existing literature and exposure limits), but the potential occupational exposure for each training scenario should consider both concentrations and exposure duration [54, 55].

3.1. Six Cycle Experiments (Measurements at 0.9 m from the Floor)

For all training fuels and all compounds that were quantified, measurements at the rear instructor location were typically higher than the front instructor location despite being farther from the source and behind the baffle. Air concentrations of benzene (IARC Group 1) were consistently the highest among all BTEXS compounds for each fuel type and sample location (Table 3). Benzene was the only

Table 3
Benzene, Toluene, Ethylbenzene, Xylenes and Styrene (BTEXS) Concentrations at the Front and Rear Instructor Location Located 0.9 m from the Floor Inside the Fire Behavior Lab and at the Outside Instructor Location in the 6-Cycle Experiments

	Front		Rear		Outside	
	Median	Range	Median	Range	Median	Range
Benzene (mg/m^3)						
Fiberboard	19	14–28	72	43–100	0.59	< 0.15–0.84
OSB	89	43–200	220	77–330	1.1*	< 0.20–1.2
Pallets	98	18–140	100	46–140	0.65	< 0.13–1.3
Particle Board	51	31–94	170	47–220	< 0.19	< 0.16–1.6
Plywood	37	19–42	150	120–200	< 0.19	< 0.18–2.1
Toluene (mg/m^3)						
Fiberboard	4.0	2.9–5.6	15	8.4–23	< 0.37	< 0.29−< 0.40
OSB	24	11–53	57	20–89	< 0.40*	< 0.39−< 0.41
Pallets	25	4.4–38	34	12–47	< 0.29	< 0.25−< 0.35
Particle Board	12	7.6–23	43	11–56	< 0.35	< 0.31−< 0.40
Plywood	8.8	4.3–10	35	30–50	< 0.39	< 0.37–0.53
Ethylbenzene (mg/m^3)						
Fiberboard	0.48	0.43–0.76	1.5	1.0–2.9	< 0.37	< 0.29−< 0.40
OSB	2.9	1.3–7.0	7.5	2.5–11	< 0.40*	< 0.39−< 0.41
Pallets	3.5	0.69–5.5	4.9	1.9–5.4	< 0.29	< 0.25−< 0.35
Particle Board	1.4	0.96–2.6	5.3	1.2–7.0	< 0.35	< 0.31−< 0.40
Plywood	1.1	0.50–1.2	4.3	3.8–6.1	< 0.39	< 0.35−< 0.40
Xylenes (mg/m^3)						
Fiberboard	1.1	0.83–1.3	4.0	2.4–5.8	< 0.74	< 0.60−< 0.79
OSB	3.9	2.5–15	16	5.5–33	< 0.80*	< 0.79−< 0.81
Pallets	6.8	2.0–10	10	5.1–15	< 0.59	< 0.51−< 0.70
Particle Board	5.4	2.8–9.2	14	2.9–25	< 0.75	< 0.62−< 0.79
Plywood	2.7	1.4–3.5	14	10–17	< 0.76	< 0.70−< 0.79
Styrene (mg/m^3)						
Fiberboard	3.3	2.0–4.2	8	5.5–16	< 1.8	< 1.4−< 2.0
OSB	14	6.9–34	37	14–55	< 2.0*	< 2.0
Pallets	16	2.9–24	19	6.7–25	< 1.5	< 1.3−< 1.8
Particle Board	8.2	5.0–13	25	7.7–31	< 1.9	< 1.6−< 2.0
Plywood	5.8	2.7–7.5	22	16–32	< 1.9	< 1.7−< 2.0

Five samples ($N = 5$) were collected for each fuel and location other than where indicated (*$N = 4$). Results shown with the less than symbol (<) are below the reporting limit (RL) and RL is provided. Median sampling times were: 24:54 for fiberboard, 21:40 for OSB, 31:12 for pallets, 23:46 for particle board and 24:02 for plywood. The percentage of the ventilation cycles where the fire dynamics training objectives were determined to be met were 55% for fiberboard, 94% for OSB, 73% for pallets, 94% for particle board and 76% for plywood [48]

BTEXS compound with a median concentration above the detection limit at the outside instructor location. Benzene concentrations at both interior locations were well above the NIOSH short term exposure limit (STEL) of 3.2 mg/m^3 (1 ppm), while none of the outside instructor location measurements reached this level. At the rear instructor location, the highest median concentrations of all BTEXS were measured during experiments conducted with OSB. However, for the front instructor location, pallet experiments resulted in the highest median concentrations of all BTEXS. The fiberboard training scenarios resulted in the lowest median concentration of all BTEXS at both sample locations inside the structure, in part because the smoke production from fiberboard decreased to the point where rollover could not be reliably generated after the third ventilation cycle.

For the three aldehydes analyzed, measurements at the rear instructor location were also typically higher than the front instructor location (Table 4). Regardless of the fuel type, acetaldehyde was the dominant aldehyde by concentration inside the structure, while formaldehyde (IARC Group 1) was the only species consistently measured above detection limits at all sampling locations. For all training

Table 4
Formaldehyde, Acetaldehyde and Acrolein Concentrations at the Front and Rear Instructor Location Located 0.9 m from the Floor Inside the Fire Behavior Lab and at the Outside Instructor Location in the 6-Cycle Experiments

	Front		Rear		Outside	
	Median	Range	Median	Range	Median	Range
Formaldehyde (mg/m^3)						
Fiberboard	21	14–25	44	34–68	0.78	< 0.36–1.90
OSB	34	15–83	47	32–88	0.43	< 0.37–1.80
Pallets	33	22–58	48	25–61	1.10	0.40–1.60
Particle Board	8	< 1.4–11	2	< 1.4–2	0.90	0.39–1.50
Plywood	16	11–33	49	10–72	0.67	0.51–2.40
Acetaldehyde (mg/m^3)						
Fiberboard	20	13–27	91	56–120	< 0.76	< 0.60–0.70
OSB	98	30–220	160	60–380	< 0.75	< 0.74–0.91
Pallets	76	26–110	170	81–200	< 0.63	< 0.46–1.7
Particle Board	37	29–90	130	110–210	< 1.2	< 0.59–1.6
Plywood	18	15–41	120	22–200	< 0.78	< 0.72–2.0
Acrolein (mg/m^3)						
Fiberboard	3.5	2.2–5.3	15	12–31	< 0.72	< 0.56–< 0.79
OSB	14	4.2–43	32	12–77	< 0.75	< 0.74–< 0.82
Pallets	16	6.2–26	24	15–27	< 0.56	< 0.46−< 0.68
Particle Board	7.5	5.2–24	27	16–49	< 0.70	< 0.65−< 1.2
Plywood	3.4	2.0–8.2	21	4.1–36	< 0.73	< 0.69−< 0.78

Five samples ($N = 5$) were collected for each fuel and location. Results shown with the less than symbol (<) are below the reporting limit (RL) and RL is provided. Median sampling times were: 24:54 for fiberboard, 21:40 for OSB, 31:12 for pallets, 23:46 for particle board and 24:02 for plywood. The percentage of the ventilation cycles where the fire dynamics training objectives were determined to be met were 55% for fiberboard, 94% for OSB, 73% for pallets, 94% for particle board and 76% for plywood [48]

fuels other than particle board, formaldehyde was consistently measured two orders of magnitude above the NIOSH STEL (0.123 mg/m^3 (0.1 ppm)) at both sample locations inside the structure. The median formaldehyde concentrations measured at the rear instructor location was relatively consistent—ranging between 44 mg/m^3 and 49 mg/m^3—for all training fuels other than particle board. Formaldehyde was detected at the outside location, with median values above the NIOSH STEL for all fuel types (and highest for fires involving pallets). Acrolein concentrations measured inside the structure were also frequently an order of magnitude above the NIOSH STEL (0.7 mg/m^3 (0.3 ppm).

1,3-butadiene (IARC Group 1) results closely resemble the BTEXS patterns described earlier with OSB experiments resulting in the highest concentrations and fiberboard resulting in the lowest concentrations at the rear location (Table 5). Median values at the rear instructor location for all fuels exceeded the OSHA PEL STEL for 1,3-butadiene of 11.0 mg/m^3 (5 ppm). Median gas concentrations of hydrochloric acid were higher during pallet experiments than the other fuels for the interior sampling locations. Concentrations of methyl isocyanate was considerably higher during the particle board-fueled fires than any of the other fuels, and all samples collected from inside the training structure during the particle board experiments exceeded the ACGIH excursion limit (230 μg/m^3).

Total PAH concentrations (Table 6), like the other analytes, were typically an order of magnitude lower outside training structure than inside (note that samples at the front instructor location were excluded because of high breakthrough due in part to extreme temperatures impacting this specific sorbent tube design at that location). For the rear instructor sample location, the plywood and pallet fueled experiments resulted in the highest median concentrations of PAHs, while fiberboard and OSB experiments had the lowest. For all fuel types, total PAH concentrations measured inside the structure exceeded the ACGIH excursion limit for coal tar pitch volatiles (1 mg/m^3), yet median values at the outside instructor location were well below this limit. Potentially carcinogenic PAHs typically comprised between 55% and 65% of total PAHs, with naphthalene (IARC Group 2B) the largest contributor (53%–60% of Total PAHs). The trends in benzo(a)pyrene equivalent toxicity and mutagenicity estimates were similar to the total PAH trends, with plywood and pallet-fueled experiments resulting in the highest median quotients (measured from rear location). A breakdown of relative contribution of each PAH compound to the total PAH and to benzo(a)pyrene equivalent toxicity based on median values from all 25 experiments can be found in supplemental mateirals (Figure S1).

3.2. Three Cycle Experiments (Measurements at 0.3, 0.6, 0.9 m from the Floor)

A follow up series of three-cycle experiments allowed for more consistent comparison with similar fire behavior for fiberboard and OSB fuels as well as the opportunity to study the impact of the potential control measure of positioning firefighters lower in the observation area. For these experiments, BTEXS and

Table 5
1,3-Butadiene, Hydrochloric Acid, Methyl Isocyanate and Dimenthyl Phthalate Concentrations at the Front and Rear Instructor Location Located 0.9 m from the Floor Inside the Fire Behavior Lab and at the Outside Instructor Location in the Six-cycle Experiments Using the Fire Behavior Lab

	Front		Rear		Outside	
	Median	Range	Median	Range	Median	Range
1,3 Butadiene (mg/m^3)						
Fiberboard	2.8	2.0–5.3	15	< 0.72–26	< 0.15*	< 0.12–0.18
OSB	22	8.5–73	65	14–130	< 0.17	< 0.15–0.22
Pallets	17	5.1–26	49	12–52	0.21	< 0.10–0.53
Particle Board	11	3.4–20	52	42–73	< 0.25	< 0.12–0.69
Plywood	3.2	1.7–8.5	30	25–57	< 0.16	< 0.15–0.65
Hydrochloric Acid (mg/m^3)						
Fiberboard	1.1	0.76–1.4	< 1.1	< 0.69–1.8	< 0.85*	< 0.72–< 1.0
OSB	1.3	< 0.78–2.0	< 1.0	< 0.73–2.2	< 1.0	< 0.82–< 1.1
Pallets	1.9	0.73–4.6	2.8	1.6–3.6	< 0.73	< 0.61–< 0.84
Particle Board	1.3	< 0.73–1.7	2.2	< 1.0–3.1	< 0.91*	< 0.84–< 1.0
Plywood	< 1.1	< 0.87–1.7	0.9	< 0.85–2.8	< 0.94	< 0.88–< 1.0
Methyl Isocyanate (µg/m^3)						
Fiberboard	17	7.5–20	17	11–50	< 1.1	< 0.93–< 1.2
OSB	26	6.2–32	22	17–29	< 1.2	< 1.2–1.5
Pallets	23	16–27	32	18–45	< 0.91	< 0.71–< 1.0
Particle Board	760	380–1500	1100	570–1600	19	5.3–120
Plywood	18	11–34	21	13–25	< 1.2	< 1.1–2.7
Dimethyl phthalate (mg/m^3)						
Fiberboard	< 0.33*	< 0.28–< 0.40	< 0.37*	< 0.36–0.62	< 0.33*	< 0.29–< 0.39
OSB	< 0.41	< 0.38–1.1	0.8	< 0.41–1.8	< 0.38	< 0.36–< 0.40
Pallets	< 0.29	< 0.23–< 0.33	0.4	< 0.27–1.9	< 0.28	< 0.24–0.32
Particle Board	< 0.36	< 0.33–0.54	0.6	< 0.33–1.1	< 0.35	< 0.30–< 0.37
Plywood	< 0.35	< 0.34–< 0.40	0.6	< 0.40–1.0	< 0.38	< 0.34–< 0.40

Five samples (N = 5) were collected for each fuel and location other than where indicated (*N = 4). Results shown with the less than symbol (<) are below the reporting limit (RL) and RL is provided. Median sampling times were: 24:54 for fiberboard, 21:40 for OSB, 31:12 for pallets, 23:46 for particle board and 24:02 for plywood. The percentage of the ventilation cycles where the fire dynamics training objectives were determined to be met were 55% for fiberboard, 94% for OSB, 73% for pallets, 94% for particle board and 76% for plywood [48]

aldehyde concentrations (Table 7) and PAHs (Table 8) were collected at the rear instructor location only at 0.9 m, 0.6 m, and 0.3 m from the structure floor.

In contrast to the six-cycle experiments, medians and ranges of BTEXS and aldehyde concentrations at the 0.9 m level were not markedly different between fiberboard and OSB, with the exception that three replicate formaldehyde concentrations were lower for OSB-fueled fires than the three fiberboard-fueled fires. The average concentrations of these compounds were generally higher than those reported for the six-cycle experiments, although the three cycle experiments were markedly shorter in duration (Table 2). Median gas concentrations of BTEXS at

Table 6
Summary Polycyclic Aromatic Hydrocarbon (PAH) Results at the Rear Instructor Location Located 0.9 m from the Floor Inside the Fire Behavior Lab and at the Outside Instructor Location in the 6-Cycle Experiments Using the Fire Behavior Lab

	Rear		Outside	
	Median	Range	Median	Range
$\sum$ **PAH** (mg/m^3)				
Fiberboard	7.8	6.5–12.1	0.333	0.044–0.412
OSB	9.1	7.6–13.4	0.370	0.048–0.732
Pallets	14.4	6.0–33.7	0.291	0.045–0.643
Particle Board	11.9	6.4–17.6	0.123	0.071–1.150
Plywood	22.2	6.9–28.4	0.056	0.053–1.374
$\sum$**PAH$_{carc}$**/$\sum$**PAH**				
Fiberboard	59.8%	57.2%–66.3%	61.0%	52.9%–64.6%
OSB	61.1%	59.2%–62.8%	61.4%	53.0%–64.1%
Pallets	63.9%	54.1%–65.9%	64.0%	62.3%–66.7%
Particle Board	64.7%	61.7%–70.5%	65.5%	63.1%–67.6%
Plywood	63.0%	59.7%–66.0%	63.1%	57.6%–63.8%
BaP_TEQ				
Fiberboard	0.181	0.093–0.317	0.018	0.017–0.019
OSB	0.208	0.170–0.318	0.019	0.018–0.027
Pallets	0.326	0.121–0.684	0.014	0.011–0.022
Particle Board	0.223	0.128–0.436	0.017	0.013–0.031
Plywood	0.515	0.153–0.695	0.018	0.016–0.034
BaP_MEQ				
Fiberboard	0.163	0.081–0.290	0.007	0.005–0.009
OSB	0.191	0.150–0.287	0.008	0.006–0.017
Pallets	0.267	0.106–0.762	0.005	0.004–0.013
Particle Board	0.201	0.115–0.378	0.006	0.005–0.022
Plywood	0.492	0.135–0.620	0.006	0.006–0.025

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

$\sum$**PAH** total concentration of PAHs, $\sum$**PAH$_{carc}$**/$\sum$**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 PAH measurements, the front instructor location results were excluded due to high breakthrough. 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 S1). Median sampling times were: 24:54 for fiberboard, 21:40 for OSB, 31:12 for pallets, 23:46 for particle board and 24:02 for plywood. The percentage of the ventilation cycles where the fire dynamics training objectives were determined to be met were 55% for fiberboard, 94% for OSB, 73% for pallets, 94% for particle board and 76% for plywood [48]

the 0.9 m height were an order magnitude higher than the levels measured 0.6 m and 0.3 m from the floor.

Total PAH concentrations (as well as TEQs and MEQs) at the 0.9 m height in the three-cycle experiment were higher in magnitude, but displayed a similar trend, as the comparable measurements in the six-cycle experiments. Interestingly, the median total PAH concentrations at 0.3 m height were greater than at the 0.6 m height for the fiberboard-fueled experiments driven by a higher concentra-

Table 7
Benzene, Toluene, Ethylbenzene, Xylenes and Styrene (BTEXS) and Aldehyde Concentrations at the Rear Instructor Location in the Fire Behavior Lab Located 0.3, 0.6, and 0.9 m from the Floor in the Three-cycle Experiments

	0.9 m from floor		0.6 m from floor		0.3 m from floor	
	Median	Range	Median	Range	Median	Range
Benzene (mg/m^3)						
Fiberboard	270	170–370	16	11–27	12	7.1–23
OSB	260	160–570	12	10–25	10	3.8–19
Toluene (mg/m^3)						
Fiberboard	52	35–75	3.4	2.1–5.6	2.3	1.2–4.9
OSB	63	40–160	2.9	2.5–5.7	2.5	0.76–4.3
Ethylbenzene (mg/m^3)						
Fiberboard	5.9	4.8–8.7	< 0.54	< 0.52–0.77	< 0.55	< 0.53–0.66
OSB	8.9	5.2–20	< 0.52	< 0.52–0.81	< 0.56	< 0.53–0.62
Xylenes (mg/m^3)						
Fiberboard	16	11–27	< 1.1	< 1.0–1.4	< 1.1	< 1.1
OSB	19	13–54	< 1.0	< 1.0–1.5	< 1.1	< 1.1–1.1
Styrene (mg/m^3)						
Fiberboard	38	25–52	2.7	< 2.6–4.0	< 2.8	< 2.6–3.3
OSB	45	26–93	< 2.6	< 2.6–3.9	< 2.8	< 2.6–2.9
Formaldehyde (mg/m^3)						
Fiberboard	52	52–59	14	10–33	6.9	2.0–12
OSB	39	27–40	11	11–16	8.8	4.6–13
Acetaldehyde (mg/m^3)						
Fiberboard	78	69–93	19	15–35	10	< 3.5–14
OSB	72	46–140	18	11–29	14	6.6–20
Acrolein (mg/m^3)						
Fiberboard	13	13–14	< 3.2	< 3.1–7.0	< 3.4	< 3.2– < 3.5
OSB	16	8.3–31	< 3.3	< 3.0–5.6	< 3.5	< 3.1–4.4

Three samples (N = 3) were collected for each fuel and location. Results shown with the less than symbol (<) are below the reporting limit (RL) and RL is provided. Median sampling times were: 14:56 for fiberboard and 16:42 for OSB

tion of vapor phase PAHs near the floor. On the other hand, TEQ and MEQ were lower near the floor as PAHs in the particle phase dominate these calculations.

4. Discussion

This study allowed us to characterize airborne concentrations of several chemicals during a common fire training scenario using representative fuel materials. Area gas samples were collected at different instructor locations and heights to provide a better understanding of potential exposures at those locations. The sampling results indicate that airborne contaminants during live-fire training scenarios can exceed applicable short-term occupational exposure limits but vary considerably

Table 8
Summary Polycyclic Aromatic Hydrocarbon (PAH) Results at the Rear Instructor Location in the Fire Behavior Lab located 0.3, 0.6, and 0.9 m from the Floor in the Three-cycle Experiments

	0.9 m from floor		0.6 m from floor		0.3 m from floor	
	Median	Range	Median	Range	Median	Range
$\sum$ **PAH** (mg/m^3)						
Fiberboard	13.2	11.6–20.1	4.6	4.2–9.6	7.8	5.8–8.7
OSB	17.0	6.0–27.0	3.8	3.7–6.6	2.1	0.9–5.3
$\sum$**PAH$_{carc}$/$\sum$PAH**						
Fiberboard	61.1%	59.6%–64.0%	58.9%	56.6%–59.1%	61.9%	59.6%–71.9%
OSB	56.8%	46.9%–62.7%	61.1%	60.3%–62.9%	57.8%	37.4%–62.6%
BaP_TEQ						
Fiberboard	0.312	0.257–0.398	0.130	0.121–0.203	0.097	0.097–0.172
OSB	0.328	0.232–0.603	0.092	0.090–0.136	0.084	0.066–0.094
BaP_MEQ						
Fiberboard	0.354	0.295–0.450	0.141	0.127–0.226	0.094	0.093–0.187
OSB	0.363	0.269–0.664	0.088	0.084–0.145	0.086	0.059–0.095

Three samples ($N = 3$) were collected for each fuel and location

$\sum$**PAH** total concentration of PAHs, $\sum$**PAH$_{carc}$**/$\sum$**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.2). Median sampling times were: 14:56 for fiberboard and 16:42 for OSB

due to day-to-day differences in environmental conditions (e.g., humidity and wind), instructors' positioning, as well as the fuel package utilized. These results reinforce the need to maintain airway protection whenever operating in and around the Fire Behavior Lab because even short-term removal of SCBA could potentially result in over-exposures. High concentrations of these compounds, many of which are known, probable and/or possible carcinogens, also present a risk for dermal contamination via penetration around gaps in PPE and/or from cross contamination when handling PPE after firefighting.

In Part A of this series, we characterized the fidelity of the fire dynamics training objectives generated when utilizing each of these fuels in the Fire Behavior Lab training structure along with the thermal exposure risk for firefighting students and fire instructors [48]. To achieve training objectives for six ventilation cycles in the Fire Behavior Lab, the most consistent fire dynamics were demonstrated with the OSB fuel followed by particle board and plywood, with fiberboard and pallets resulting in less repeatable flashover and rollover demonstration. However, the OSB fuels resulted in the highest heat fluxes with pallets resulting in the lowest. It was found that fuel substitutions may impact thermal risk for students and instructors but can also impact the consistency of the fire dynamics being presented to the firefighting students. A more impactful reduction in thermal risk may be created by controlling firefighters' elevation

within the training structure, regardless of the training fuel used. Increasing the distance from the fire area had the largest impact in reducing thermal risk to instructors.

Several factors can contribute to the variability in sampling time, fire dynamics and ultimately, the magnitude of combustion products. Fuel preparation and fuels sets were carefully controlled for each experiment. All materials used for the five replicates of each fuel were delivered at the same time from the same manufacture and distributor. Fuels were carefully loaded by trained instructors and researchers to be as identical as possible. The training structure was allowed to cool to ambient conditions prior to reloading the fuels. The ignition scenario and ventilation conditions were scripted, controlled and repeatable. However, the ambient conditions, including air temperature, humidity, pressure, wind speed and direction and, in some cases, precipitation, were not possible to control with the outdoor training prop. Each of these factors can impact not only fire development, but also the ventilation of smoke from the training structure. The 0.9 m sampling height, where the head height of a sitting instructor is assumed to be located, will be near the smoke layer that descends to the fire area floor, so small changes in smoke volume and lift can have dramatic impacts on the exposure levels at this height. However, the experimenal design with randomized fuel order should help account for any unintended biases.

4.1. *Impact of Fuel Selection in Fire Behavior Lab*

PAHs are the most common class of compounds reported in the fire service exposure literature and the range of PAHs measured in the Fire Behavior Lab were consistent with those measured to date. Fent et al. measured total PAH personal gas concentrations (sampled by personal samplers located at chest height) with medians ranging from 2.78 mg/m^3 for fire instructors conducting pallet and straw fuels scenarios in a concrete training structure to 34.0 mg/m^3 for firefighters in an OSB, pallet, and straw fueled scenario in a metal container based structure [41]. In comparison, the 31 experiments here resulted in total PAH concentrations that ranged from 6.0 mg/m^3 to 33.7 mg/m^3. Median sampling times in our study (Table 2) were similar to the sampling times for instructors (25–30 min) but longer than the sampling times for firefighters (9 to 12 min) [41]. Personal gas samples collected using similar methods from firefighters responding to controlled residential fires measured a median of 23.8 mg/m^3 total PAHs (range: 7.46 mg/m^3 to 78.2 mg/m^3) and 17.8 mg/m^3 total PAHs (range: 9.77 mg/m^3 to 43.8 mg/m^3) for firefighters assigned to attack and search job assignments, respectively [16]. Other studies have reported total PAH concentrations of 0.43 mg/m^3 to 2.70 mg/m^3 for particle board-fueled training fires in Australia [42], 75 mg/m^3 to 180 mg/m^3 for particle board-fueled training fires also in Australia [47], and 19 mg/m^3 to 41 mg/m^3 for chipboard-fueled training fires in Sweden [21]; although it should be noted that the latter authors summed 22 PAHs as opposed to 16 here.

Calculation of toxic and mutagenic equivalencies for the PAH concentrations provided another means of comparing the relative health risk from these training fires. It is possible that the PAH composition generated when using different train-

ing fuels could be more heavily weighted towards the more carcinogenic compounds (e.g., benzo[a]pyrene), thus resulting in higher TEQ or MEQ estimates. However, the PAH composition was similar across the training fuel types, with approximately 60% in the IARC Group 1, 2A, or 2B categories and with TEQ and MEQ estimates following similar trends as the total PAH concentrations. Nevertheless, it is interesting to note that although naphthalene was the dominant species (accounting for > 50% of total PAHs), benzo[a]pyrene and dibenzo[a,h]anthracene were the most impactful PAHs on a toxicity basis (Figure S1). Kirk and Logan used the same TEQ calculation on personal gas concentrations of PAHs measured during particle board-fueled training fires and found much lower TEQs (0.044 mg/m^3 to 0.063 mg/m^3) than we did at the rear of the structure for the same fuel (0.223 mg/m^3) and different fuels (0.093 mg/m^3 to 0.695 mg/m^3) [42]. However, this difference was driven primarily by overall lower PAH concentrations in the Kirk and Logan study which may be attributed to differences in structure geometry, fuel and ventilation locations and/or location of gas sample collection.

Area gas concentrations of benzene measured at the 0.9 m working height inside the structure (median range of 19 mg/m^3 to 270 mg/m^3) were generally higher than the personal gas concentrations measured in Fent et al. where the median range was 9.6 mg/m^3 to 29 mg/m^3 for instructors and 10.8 mg/m^3 to 101 mg/m^3 for firefighters during live-fire exercises involving different fuel packages [41]. Laitinen et al. reported area gas concentrations of benzene ranging from 0.624 mg/m^3 for pure spruce and pine wood-fueled fires to 0.998 mg/m^3 for chipboard-fueled fires (that also included some polyurethane foam and kerosene) to 2.516 mg/m^3 for conifer plywood-fueled fires [39]. Kirk and Logan also reported comparably lower gas concentrations of benzene during compartment fire behavior training sessions using particle board (4.5 mg/m^3 to > 7.8 mg/m^3) [43]. However, Fent et al. measured personal gas concentrations of benzene from search and attack firefighters who operated at controlled residential fires (median 121 mg/m^3 and 129 mg/m^3, respectively with peak concentrations near 1000 mg/m^3 for both groups) that were well within the ranges reported here [16].

All fuels other than particle board produced similar levels of formaldehyde at the rear instructor location at the 0.9 m height (median range of 39 mg/m^3 to 52 mg/m^3 compared to 2 mg/m^3 for particle board). Fent et al. measured comparable levels of formaldehyde between a pallet and straw scenario and one type of OSB (4.6 mg/m^3 vs 4.5 mg/m^3—though a second type of OSB had higher formaldehyde concentrations (35.2 mg/m^3)) [41]. 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' [39]. Kirk and Logan also reported lower gas concentrations of formaldehyde during compartment fire behavior training sessions (0.53 mg/m^3 to 5.0 mg/m^3) [43]. The acrolein concentrations measured inside the Fire Behavior Lab structure at the 0.9 m height (median range of 3.4 mg/m^3 to 32 mg/m^3) were similar to the levels measured during live-fire exercises in Fent et al. where the median range was 4.9 mg/m^3 to 60.6 mg/m^3 [41].

The pallet-fueled scenario resulted in the highest concentrations of hydrogen chloride. Chlorine and other halogens occur in nature and may be absorbed by trees. However, it is unknown why timber used in pallets would contain more chlorine than timber used in the other wood-based products. This result does corroborate the findings in Fent et al. where the pallet and straw fire training scenario produced higher concentrations of hydrogen fluoride and hydrogen chloride than the scenarios that incorporated OSB [41].

Another notable finding of this study was the relatively high concentration of methyl isocyanate during the particle board-fueled training fires. Particle board (along with other wood-based products such as OSB and plywood) may contain isocyanate-based glues or polymers, and materials in this family may produce methyl isocyanate (as well as other isocyanate compounds) upon combustion [56, 57]. Methyl isocyanate is also used in the production of carbamate pesticides. While the straw used in this study was reportedly 'pesticide free', the authors ran a follow up experiment using only straw in the ignition barrel and detected similar magnitudes of methyl isocyanate as reported in Table 3 for the training fuels other than particle board. In all five particle board experiments, the ACGIH excursion limits were exceeded in the front and the rear instructor location, while values remained typically an order of magnitude below this limit in experiments with the other four training fuels. The source of the dimethyl phthalate contaminants is unknown. However, phthalates are present in numerous consumer products containing polymers.

4.2. Evaluation of Potential Control Measures

We hypothesized that utilizing a training fuel package that incorporated solid wood products (pallets) along the wall and ceiling would result in a lower concentration of airborne contaminants than fuel packages that utilized panelized wood based products with resins and/or waxes (low density wood fiberboard, OSB, particle board, plywood). We sought to address this question using a common training structure described in NFPA 1402 and 1403 and then altering the fuel packages using materials that are commonly employed in fire service training. For the six-cycle experiments, training fires involving fiberboard, which utilizes wax-based binders, resulted in some of the lowest concentrations of many compounds (including PAHs and VOCs). However, there were no notable differences in chemical concentrations between OSB and fiberboard fuel sets when in the shorter, three-cycle experiments. At the same time, fires involving brand new pallets resulted in the second highest total PAH concentrations at the rear instructor location and the highest BTEXS and acrolein concentrations at the front instructor location. The pallet and fiberboard fuel packages resulted in the longest six-cycle test scenarios. As noted previously, both chemical concentration and exposure duration are important factors that may impact biological uptake (along with PPE protection and other factors). Additionally, as described in Stakes et al., the fire behavior encountered with these two fuel packages were the least consistent in their ability to achieve the underlying training objectives, which can impact the training experience and lessons learned by students [48].

On the basis of the gas sampling results alone, it may be difficult to select one fuel over another. In comparing the median concentrations across the six-cycle experiments (at the rear instructor location), OSB-fueled fires produced the highest median concentrations of BTEXS and 1,3 butadiene, plywood-fueled fires produced the highest PAH concentrations, particle board-fueled fires produced the highest methyl isocyanate concentrations, and pallet-fueled fires produced the highest hydrogen chloride concentrations. All fuels other than particle board produced similarly high levels of formaldehyde at the rear instructor location. Fiberboard-fueled fires often produced the lowest concentrations of contaminants, likely because the burning rate of the fiberboard decreased to the point where rollover could not be reliably generated after the third ventilation cycle. This explanation is reinforced by the fact that little difference was observed among PAH, BTEXS, and aldehyde concentrations for shorter (three-cycle) experiments involving OSB and fiberboard. Further research is necessary to determine if a substitute fuel can be developed that provides high quality training environments yet results in lower concentrations of airborne contaminants (particularly those that may be carcinogenic). Substitution controls are considered among the most effective under the NIOSH hierarchy of controls [58]. Finding such a substitute would likely reduce not just potential inhalation exposures (i.e., when respiratory protection is doffed), but also potential dermal exposures from ingress of contaminants through turnout gear or from cross-contamination when handling contaminated PPE. In the meantime, utilizing airway protection whenever in smoke and good hygiene and cleaning practices can be effective control measures for reducing risk.

When mounting training fuels on the ceiling, oxygen concentrations available for combustion will typically be below 10% and often below 5% [48], resulting in fire effluent with large amounts of products of incomplete combustion. It is possible that different results would be found with other fuel arrangements such as fuels loaded in a ground-level hopper in the middle of the training room. However, mounting fuels on the ceiling is common in many compartment fire behavior training structures (e.g., [43, 59]), metal container based training structures (e.g., [41]) and other Class A burn buildings, where fuels are supported at or near the ceiling by chains or steel fuel racks. This mounting arrangment is commonly employed to create smoke opacity and ignition/rollover behavior that firefighters might encounter in ventilation limited fires in real world response. Such conditions can provide important controlled training environments that assist to prepare firefighters for the dynamic fireground.

This study also provided the opportunity to characterize the impact of administrative control measures which would relocate fire instructors or firefighters that work in the structure. The gas sampling results indicate that instructors at the rear location will be working in an area with higher airborne concentrations of the compounds studied than the front instructor location (contrary to the relatively lower air temperatures and heat fluxes at the rear location [48]). This phenomenon likely results from heated smoke traveling along the ceiling, impacting the relatively cool vertical obstruction at the back of the structure, and then descending onto the instructor. This differs from the front location where combustion byproducts remain at elevated heights and temperature. While the front instructor

is typically charged with teaching the class and running the scenario in the structure, the rear instructor is most often responsible for operating the vents. However, these vents can be operated from outside the structure—where airborne exposures may be two to three orders of magnitude lower. Also, by remaining outside the structure, the rear instructors would not experience the spikes in pressure when the vents were closed [48]. More research is needed to understand if such pressure spikes could provide a mechanism for driving airborne contaminants underneath the firefighters' PPE through gaps in protection. Even though airborne concentrations of all compounds were lower outside of the structure, potential exposures remain, particularly for formaldehyde, which had median concentrations above the NIOSH STEL for all fuel types. Thus, students and instructors should continue to use PPE—and particularly SCBA—even when operating immediately outside of the training structure.

The follow up three-cycle experiments allowed us to evaluate the impact of height on potential exposures. While most data were collected 0.9 m above the floor to simulate approximate head height for a kneeling/crouching fire instructor, it is conceivable that instructors could get even lower inside the structure, especially with structural modifications such as using a taller container in the observation area or by having instructors and students lie on the ground in the observation area (anecdotally, this practice was employed when these training structures were first being utilized). Overall, gas concentrations of BTEXS, aldehydes and many of the higher molecular weight PAHs were reduced when sampling at 0.3 m and 0.6 m from the floor. The one outlier in this trend was for the lower molecular weight PAHs in the fiberboard experiments where higher median concentrations were measured at 0.3 m vs. 0.6 m height. Further study is needed to understand the potential cause for this unexpected finding. TEQ and MEQ, which are better estimates of potential toxicity than individual PAH concentrations, were approximately two to four times lower at 0.6 m and 0.3 m than 0.9 m height. Thus, orienting instructors and firefighters in a manner that keeps them lower in the observation chamber will likely reduce their exposure to many hazardous emissions. Some training academies have installed benches in their Fire Behavior Lab to make it more comfortable to observe the scenario, but this should be reconsidered if it increases head height (above 0.9 m) due to potential increased thermal and chemical exposure risk. It is possible that the design of the structure could be modified to lower the observation area using a taller container. As with any change in training environments, such modifications should be investigated holistically, considering impact on instructional objectives and other possible risks, such as larger potential fall distances from the fire area to the observation area.

4.3. Limitations and Future Work

While this study provides the most complete characterization of compounds measure during live fire training involving different types of fuels to date, there are important limitations to this work. Changes in weather and ambient conditions throughout the study likely contributed to variability in results. This might explain why variability in air concentrations for some compounds were greater

within a fuel package than between fuel packages. Conducting experiments in a large indoor lab environment would allow control over these ambient conditions and may allow tests of statistical significance to be conducted. However, the training structure is most commonly used in an outdoor environment, so the variability reported here is representative of the typical use case. The fuels selected in this work are among the most common in the fire service today, but there are other materials that can be used for training fires.

Future research should expand upon this work to study how different fuels and other control interventions during live-fire training impact the biological uptake of chemicals by firefighters and instructors. Such research should consider the holistic impact of these control measures on chemical and thermal exposure as well as learning objectives. A similar study should be conducted using alternative fuel orientations particularly with fuels lower in the compartment and with more ventilation (such as a traditional hopper in the middle of a concrete structure). It is likely that differences in individual fuel components may have more impact on evolution of products of combustion when utilized in more well ventilated burning conditions. Studies should also be conducted using combinations of these fuels, such as using fiberboard and pallets on the structure ceiling, which has been found to improve fire dynamics repeatability compared to these fuels used individually. Future research should evaluate the elemental composition and yields of training fuels in order to characterize exposure hazard using bench scale methods that can then be coupled with these large-scale results. Finally, a tradeoff analysis should be conducted to evaluate the fire dynamics training benefit compared to the exposure risk presented by firefighters' and instructors' immersion in the vent limited fire conditions.

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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