ABSTRACT

Title of thesis:	Study of the Fidelity and Safety of the Fire Service Training Environment
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Recent firefighter line of duty deaths as a result of rapid fire progression have highlighted that there is a deficiency in firefighters' understanding of the fire dynamics created by modern, synthetic fuels on the fireground, and how their tactics may influence these conditions. In particular, the rapid growth of these modern fires, their response to ventilation, and their propensity to become underventilated have changed when compared to their legacy counterparts. Among the reasons for this gap in understanding is the way in which firefighters conduct live fire training. Typical fuels used for firefighter training, such as pallets and straw, are more typical of legacy fuels than modern, synthetic fuels, however. Recognizing this, many instructors have begun to introduce synthetic materials into live fire training, in an effort to make the training feel more realistic. While these fuels may exhibit fire behavior more representative of a room and contents fire with modern furnishings, they also create the potential for hazardous conditions for firefighters. A series of eight experiments was conducted in a concrete fire training building. Two training fuel packages were considered. The first consisted of wooden pallets and straw, a common fire training fuel. The second introduced oriented strand board (OSB) to the pallets and straw fuel package. Both of these training fuels were compared to a room with furnishings similar to those that may be found in a residential home. The results indicated that pallets and straw fail to replicate the high radiant heat flux, underventilated conditions, and rapid response to additional ventilation that was noted in the furnished room fire. Further, since the concrete training building had several built-in ventilation points, and additional ventilation resulted in no increase in thermal conditions, the pallets and straw training fires could be considered fuel limited. In the OSB experiments, on the other hand, a limited growth secondary to ventilation was observed. Thus, the OSB fires represent a more realistic simulation of a furnished room fire than the pallets and straw. In addition to increased fidelity, the OSB training fires exhibited more severe thermal conditions, which would pose a greater hazard to students and instructors than in the pallets and straw evolutions. Thus, if fire instructors should elect to include synthetic materials, such as OSB, into live fire training evolutions, additional precautions must be taken to ensure that participants are not exposed to excessive thermal conditions. Likewise, if instructors choose pallets and straw as a training fuel because of the increased margin of safety, special emphasis must be placed on the difference in fire behavior between

the training fuel and the modern, synthetic fuels that would be encountered on the fireground.

Study of the Fidelity and Safety of the Fire Service Training Environment

by

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Table of Contents

List of Figures

Chapter 1: Motivation

Several noteworthy firefighter line of duty deaths and injuries have occurred in recent years on the fireground as a result of rapid fire progression [1–4]. Among the contributing factors to these incidents was a lack of understanding of fire behavior [1–3]. Recent studies on firefighter safety [5, 6] have identified that the shift towards a higher synthetic content in modern home furnishings has resulted in fires with higher heat release rates than legacy fuels, which were composed mostly of natural materials. This shift has resulted in a more unforgiving fireground, where poorly timed actions such as uncoordinated ventilation can result in the rapid deterioration of conditions. Unfortunately, fire department tactics do not always reflect this changing fire environment. Among other considerations, the necessity for firefighters to understand the fire dynamics that they are likely to encounter on the fireground has been identified as essential for firefighter safety.

Although the fuels found in the modern residential home have evolved to become comprised mostly of synthetic materials, the fuels that firefighters use to practice live fire training are still more representative of legacy fuels. National Fire Protection Association (NFPA) 1403: *Standard on Live Fire Training Evolutions* is the NFPA document which outlines the methods that should be used and precautions that should be taken for live fire training scenarios [7]. The standard limits the types of fuels that can be used to wood based fuels. As a result of this restriction, wooden pallets and straw are a common training fuel that is used for such evolutions. Pallets and straw have long been used as an economical training fuel for fire training facilities because they are easy to procure and create a predictable fire. However, some academies and training groups have recognized that the conditions produced by these pallets and straw training fires are not representative of those observed in residential fires. Thus, in an effort to replicate the conditions experienced on the modern fire ground, these organizations have begun to incorporate different fuels into their live fire training evolutions, including engineered lumber, such as pressboard, particleboard, and oriented strand board (OSB). These engineered wood products combine glues or resins with smaller pieces of wood to form larger sheets or boards. The higher synthetic content of engineered wood produces more severe thermal conditions than traditional pallets and straw training fires, while still nominally remaining compliant with NFPA 1403.

The introduction of these new fuels into the training environment raises the issue of balancing the fidelity of training fires with the safety of participating in such burns. Many instructors assume that producing a training fire with high fidelity invloves replicating thermal conditions that are of a similar severity as those that students would encounter on the fire ground. As the training fuel package is modified to produce conditions consistent with a furnished room, the thermal environment becomes more hazardous. It is important that the thermal hazard of the training environment is considered, as several firefighter line of duty deaths have resulted from excessive thermal exposure during training evolutions [8–10]. Rather than mirroring the conditions experienced in a residential home using modern fuels, the goal should be to simulate the response of the fire to firefighter tactics. This will minimize the potential of forming bad habits as a result of low-fidelity live fire training, while still preserving a reasonable margin of safety.

This series of experiments aims to compare the fire dynamics produced by two training fuels with the fire dynamics resultant from furniture common to a modern home. In particular, this investigation will focus on training fire evolutions in concrete buildings, similar to those found at many training academies across the United States. In addition to comparing the thermal conditions that result from the training fuels, the effect of various firefighter tactics on these conditions will be examined. The thermal hazard in locations in the training structure that firefighters may be positioned will be considered as well.

Chapter 2: Literature Review

NFPA 1403: *Standard on Live Fire Training Evolutions* outlines the requirements for live fire evolutions in acquired and fixed facility training structures [7]. The document discusses the responsibilities of the instructors, safety officers, and participants, and also provides guidelines for the types of fuels that can be included in the fuel package. The standard specifically forbids treated wood products, rubber, plastic, polyurethane foam, upholstered furniture, and chemically treated straw as fuels. Furthermore, the documents advises that the fuel load should be limited to mitigate the potential for backdraft or flashover. NFPA 1403 additionally makes several specific recommendations for acquired structure training burns. The standard recommends against the use of low-density particleboard and unidentified materials found within the structure. Furthermore, the document mandates that combustible materials not included in the fuel load should be moved to an area of the structure remote from the fire room. The 2017 Edition of NFPA 1403 additionally requires a thorough understanding of fire behavior and the impact of ventilation on fire dynamics. The standard emphasizes that students must be familiar with the basic physical and chemical concepts behind combustion and compartment fire behavior, and must be able to identify potential thermal hazards within the building. Previous versions of the standard do not discuss the importance of fire dynamics concepts [11, 12].

NFPA 1403 was developed in response to a live fire training accident in 1982 that resulted in the deaths of two firefighters in order to offer a standard means of conducting live fire operations safely in both fixed-facility and acquired burn structures. Despite the procedures and precautions contained in NFPA 1403, there have been several instances where firefighters have been killed or injured during live fire evolutions. The National Institute of Occupational Safety and Health (NIOSH) investigated several of these incidents, which are described below.

In a 2005 incident in Pennsylvania, which would attract further studies into the hazards of the training fire environment, NIOSH led an investigation into the death of a 47-year-old fire instructor. The instructor experienced a catastrophic failiure of his facepiece lens during a live-fire "Train the Trainer" course, and died of thermal injuries two days after the event. The burn building was a 2.5 story concrete block structure. Investigators attributed the facepiece failure to the high thermal conditions that were present in the basement during the evolution. The investigation emphasized the importance of using the minimum amount of fuel necessary to perform live-fire training while maintaining firefighter safety. Additionally, this incident demonstrated the dangers of repeated evolutions without allowing sufficient time between evolutions for the burn building to cool down [9].

In a 2007 incident which occurred in Maryland, a female probationary firefighter was killed during a training evolution in a vacant end-of-the-row townhouse. The scenario used approximately 12 wooden pallets and 11 bales of hay as fuel, and featured fire sets on all three floors of the townhouse. The victim was on the nozzle of the first hoseline, and was instructed to bypass the fires on the first and second floors and make an attack on the third floor fire. when the attack team reached the stairway between the second and third floors, they were overcome by the high heat conditions. The instructor and backup firefighter exited the structure through a window. The victim reached the window, but was unable to get the lower half of her body out of the window. While the instructor was trying to remove her from the fire room through the window, her mask became dislodged. She was finally removed when another instructor came up the stairs and helped her legs through the window. The victim succumbed to thermal injuries and asphyxia. NIOSH attributed the outcome of the incident to several factors, including a lack of equipment, a lack of physical fitness performance requirements, and a failure to follow the requirements of NFPA 1403 [8].

Two career firefighters were killed in a training fire in an acquired structure in Florida. The structure was a one-story, single family house with three bedrooms, two bathrooms, and a kitchen. The fire was ignited in one of the bedrooms, and had a fuel load of wooden pallets, straw, and a urethane foam mattress. Before ignition, other materials in the room, such as urethane foam padding, hollow core wood doors, and carpeting were not removed, and thus contributed to the fuel load. Four firefighters acted as interior safeties throughout the duration of the incident. The victims entered the structure first, to perform a primary search of the building. They were followed by the attack line. The victims passed the safety/ignition officer that was positioned outside of the fire room, who retreated to the living room to help the attack company while the victims proceeded to search the fire room. Before applying water, the fire room window was vented and dark, heavy smoke exited the window. The attack company began to apply water in short bursts, and one of the safety officers exited the structure, thinking that he had been "steamed." The victims remained unaccounted for for several minutes. During this time, it is suspected that the fire room flashed over. After the victims failed to acknowledge repeated attempts by the Incident Commander (IC) to contact them, the IC activated the rapid intervention team (RIT), who found the victims in the fire room. They were transported to a local hospital and pronounced dead. The investigation identified the fuel load and uncoordinated ventilation as contributing factors, noting that the use of fuel with unknown burning characteristics can lead to unexpected fire development and rapid fire progression [13].

In another line of duty death incident, A New York volunteer firefighter was killed during a simulated "mayday" scenario, where he and another firefighter were playing the simulated victims. The victim had very little training prior to the incident, and had never worn an self-contained breathing apparatus (SCBA) under live fire conditions before. The training was conducted in a vacant two story duplex. The scenario simulated two firefighters being trapped in an upstairs bedroom in one half of the duplex, and involved the engine and rescue company making entry through the other half of the duplex, breaching a wall, and rescuing the downed firefighters. The intended fuel source was a burn barrel in one of the bedrooms, but an assistant chief ignited a foam mattress when the ignition firefighter had trouble igniting the burn barrels. The ignition of the mattress led to rapid fire growth and caused conditions throughout the duplex to deteriorate. The ignition firefighter attempted to help the two trapped firefighters, but in the process lost his gloves, received burns to his hands, and was forced to exit out of a second story window. When the engine and rescue companies arrived on scene, they both acted as RIT teams, and removed the trapped firefighters from the structure. The victim was transported to a local hospital, where he was pronounced dead. The other firefighter that was removed from the structure and the ignition firefighter that jumped from the second floor were flown to a regional burn center. The investigation highlighted the importance of not using live victims during live fire training and ensuring that the fuels used in training burns are in accordance with NFPA 1403 [10].

Incidents such as these highlight the debate within the fire service about balancing safety requirements, such as those recommended in NFPA 1403, with realistic fire training that prepares recruits for the modern fire ground. Many articles published in fire service trade magazines, such as that written by Greg Fisher, emphasize the importance of conducting training that adheres to the guidelines of NFPA 1403 [7]. Fisher cautions against including loose trim, furnishings, and debris in the fuel package, as was done in acquired structure burns for many years. The inclusion of such materials, whose compostion may be unknown, can lead to unpredictable fire behavior. In addition to removing loose materials from the acquired structure, Fisher stresses discretion when determining the size of the fire set. He points out that fuel sets that are larger than the students are comfortable with may cause students to panic, invalidating the training. When constructing a fire set with pallets, Fisher highlights geometry as an important factor. The pallets and straw should be arranged in a corner so that the fuels are located as close to the ceiling of the room as possible. Such an arrangement will allow for the fire to rapidly reach a fully developed stage, and will mimic the fire dynamics of a room and contents fire. Fisher adds that it is important to monitor for window and ceiling failure during the training evolution, as these events may cause unwanted changes in fire behavior. Thus, the students' safety and comfort level should be prime considerations in the orchestration of an acquired structure training burn [14].

In an article by Kriss Garcia and Reinhard Kauffman [15], they highlight some of the challenges of conducting acquired structure training. The authors describe an instance where hours of work were put in to prepare a building for a live burn, only to find that the previous owner of the house had plastered over layers of medium-density particleboard, concealing the engineered wood board and leading to unexpected fire growth. The article presents instructions for a makeshift acquired structure, comprised of dimensional lumber and gypsum board walls. The authors maintain that this "build and burn" prop provides students with a safer and more realistic fire training experience by combining the realistic building materials and geometry of acquired structures with the predictability and more controlled environment of fixed-facility burn structures. The authors describe the standard fuel package that they use as consisting of five pallets. The first two pallets are leaned against each other diagonally, the second two are oriented vertically next to the first two, and the fifth pallet is laid across the top of the bottom four. The authors recommend that this fuel package should be placed in the center of the fire room, where it will generate enough energy to bring the room to flashover and realistic amounts of combustion products [15].

Forest Reeder presents the debate within the fire service about balancing the need for realistic training with safety requirements in his article [16]. Reeder highlights some of the frequent complaints that are voiced against the standard. Some instructors are frustrated that NFPA 1403 prohibits what they consider to be more realistic training evolutions, with more smoke and higher heat conditions. These instructors feel that the standard is too restrictive, and that the safety requirements invalidate the training experience. These instructors argue that Class A and gas-fired training fires do not create realistic smoke or heat conditions, leaving recruits unprepared for the high heat conditions frequently seen on the modern fire ground. Reeder emphasizes that the safety requirements that some see as overbearing or restrictive are necessary to prevent tragic accidents in live fire evolutions. Furthermore, building the fire sets so that heat and smoke conditions are unbearably high may instill the idea that such high heat conditions are acceptable, leaving recruits vulnerable to rapid fire events on the fire ground. Reeder maintains that control and pre-planning are important facets of a successful live fire training evolution [16].

Among the common factors among the line of duty death incidents described above is the improper use of training fuels. In several of the acquired structure burns, the addition of debris found around the house had the effect of increasing the fire size beyond what was manageable or expected. The articles by Reeder and Fisher indicate that a possible motive for these increased fuels loads was to make the training fire "hotter" and "more realistic." In the Pennsylvania Fire Academy incident, the victim was exposed to repeated, high intensity thermal exposures which resulted in the failure of his personal protective equipment (PPE). A poor understanding of the thermal conditions that these fuel loads would produce led to the deaths in these instances. In an effort to better understand the training fuels that firefighters use, a series of research studies have aimed to quantify parts of the training fire environment.

Madryzkowski et al. investigated a pair of training fires in which firefighters had been killed. The first incident occurred during an acquired structure burn in Florida, where two firefighters died while conducting a search when the fire room flashed over [13]. NIST recreated the fire room and two adjacent spaces, and evaluated the thermal conditions caused by five different combinations of fuel load and ventilation conditions. The results indicated that flashover conditions were reached for each fuel load, including the experiment where only pallets, straw,wood molding, and a hollow core door were used. Furthermore, the temperatures exceeded 260°C and the heat fluxes exceeded 20 kW/m^2 during each test, indicating that the thermal conditions in the fire room were unsurvivable for even a firefighter in full PPE. An additional experiment examined the heat release rate of the pallets and straw, which was found to be 2.8 MW [17]. The authors compared this heat release rate to the theoretical heat release rate required for flashover in the room, and found that the HRR was sufficient to cause flashover. The second incident that was investigated occurred in Pennsylvania, during a "train the trainer" class. After the last burn of the day, an instructor was found lying face-down on the floor in the basement with damage to his facepiece. He later succumbed to his injuries. NIST instrumented the burn building where the incident occurred and attempted to recreate the thermal conditions that were present at the time of the instructor's death.

Thermocouples wereThey first used a fuel load of pallets and excelsior to “preheat” the burn structure. After that, additional pallets and straw were added. When the fires peaked, the fuel was suppressed with a hose stream and the compartment was hydraulically ventilated. Once the compartment was cleared, additional pallets were added to the embers, and the process was repeated. The ambient heat flux at 1.5 m from the ceiling before the last evolution was 6 kW/m^2, and the ambient temperature in the burn structure was 150°C at 1.53 m below the ceilings. It is suspected that the actual heat flux and temperature experienced by the victim was higher than these values, since the victim was standing at the time that the damage occurred, and the upper half of his body would have been positioned higher in the room than the height at which these measurements were obtianed. Laboratory experiments indicated that 6 pallets and straw had a peak heat release rate of 4.5 MW. In both fatal training fire incidents, the thermal conditions that resulted from the fuel loads exceeded the protective capabilities of the firefighters’ personal protective equipment. This highlights the the necessity of using discretion when determining the fuel load of training fires.

Lannon and Milke [18] ran a series of CFAST [19] simulations to assess the hazards presented to firefighters during training fires. The authors compared these models to training fires experiments that had been previously conducted by the Maryland Fire Rescue Institute and the National Institute of Standards and Technology. When the data from one of the pallet burns was compared to the results of the computer model for an identical pallet configuration, the temperature and heat flux data were found to be similar. The zone model used in the simulation was

CFAST, and the simulations examined a triangular orientation of pallets and excelsior, a pile of excelsior with no pallets, stacked pallets oriented horizontally both with and without excelsior, and vertically stacked pallets with excelsior. The simulations indicated that the vertically configured pallets exhibited the highest heat release rate of the pallet configurations. Additionally, when horizontal ventilation was introduced, the temperatures and heat fluxes throughout the concrete burn building decreased rapidly. The authors also examined the effects of multiple burns in close succession. The results indicated that repeated burns precipitate more hazardous thermal conditions in later evolutions. The authors cautioned that, when conducting live fire training, instructors should allow for sufficient time between burns for the structure to cool down to safe levels.

Willi et al [20] conducted a series of experiments to quantify the thermal exposure of firefighters in a training environment. The authors constructed a portable data acquisition system that was capable of gathering heat flux and temperature data on a firefighter during a training exercise. The tests examined two types of firefighter training evolutions: scenarios conducted in concrete burn buildings, using wooden pallets and straw as a fuel load, and a metal container-based training prop known as a "flashover simulator", which had a fuel load consisting of pallets, straw, oriented strand board (OSB) and medium density particleboard. The results indicated that routine training evolutions exhibited heat fluxes on the order of 1 kW/m^2 and temperatures close to 50°C,whereas more severe exposures showed heat fluxes between 3 and 6 kW/m^2 and temperatures between 150°C and 200°C. Furthermore, the experiments showed that, in some instances, the temperature under predicted the thermal hazard that was posed by the heat flux. The authors also noted that stationary temperatures located in training buildings offered only a rough approximation of the thermal hazard to the firefighters working in those buildings.

René Rossi [21] conducted a series of experiments in firefighter training buildings in Switzerland in order to examine the effect of different thermal exposures on core temperature and sweat production. Heat flux and temperature measurements were taken in the training buildings. Rather severe peak thermal conditions were observed during the tests, noting temperatures as high as 278°C and 26 kW/m^2. More routine exposures were between 50°C and 130°C and 5 and 10 kW/m^2. The results indicated that relatively high heat fluxes were observed for rather moderate temperatures.

Thus, while a number of studies have examined the thermal hazards that firefighter students and instructors are exposed to in the training fire environment, there is a gap in the literature regarding the fidelity of these training fires, that is, the degree of exactness that the training fires adhere to a fire that may be encountered on the modern fireground. Additionally, little research has focused on new training fuels, such as OSB, particleboard, and other engineered wood products, that many training academies and organizations have begun to incorporate into fire service training. This study will attempt to bridge the gap in understanding between training fuels and fuels representative of those found in residential structures. Additionally, the relative thermal hazards of these fuels will be compared, in an effort to place into context the relative severity of these fuels.

Safety is a critical concern for live fire training scenarios. It is imperative that safety is not compromised in the pursuit of creating fire dynamics consistent with a realistic residential fire with modern fuels. This means the minimization of training-related injuries and deaths from excessive thermal exposure. Additionally, thermal conditions in which equipment, such as facepieces, helmets, and electronic equipment, may be damaged are undesirable, as the replacement of such equipment can unnecessarily burden a fire department.

Training fires are different from typical fires that the fire department may respond to in the respect that firefighters involved in suppression and search and rescue operations are not the only personnel inside the burn structure. Rather, support personnel such as instructors and stokers are actively involved in the training scenarios as well. Stokers are firefighters whose specific task is the construction and maintenance of fuel packages throughout the training evolution. In contrast to a residential fire, where the suppression team would likely be mitigating conditions with a hose line before entering the areas of the most severe thermal conditions, these instructors and stokers are often tasked with maintaining the fire, and may be positioned in or close to the fire room, possibly for extended periods of time. Thus, the threat that the thermal conditions in these areas pose to firefighters must be considered. Additionally, it is important that recruits understand that although such areas are relatively safe for habitation in the training environment, the same areas in a real fire may quickly result in death or serious injury.

A variety of methods exist for evaluating the thermal conditions to which firefighters are exposed. In general, they divide the thermal environment into either three or four classes, with the lowest class representing conditions only slightly more severe than ambient, and the highest class representing emergency conditions, tenable for only a few seconds before equipment failure, injury, or death are imminent. Some of these methods, such as the NIST Thermal Classes proposed by Donnelly et al. [22] are used primarily for the purpose of evaluating electronic equipment used by firefighters. The NIST thermal classes specify 4 classes, which are presented in Table 2.1. Since these thermal classes are focused specifically on electronic equipment, PASS alarms in particular, they are not the most appropriate for evaluating the risk of thermal injury to firefighters in training fires. Additionally, heat flux and temperature are treated separately in the NIST thermal classes, so the consideration of only one value may give an incomplete picture of the thermal threat.

Table 2.1: NIST Thermal Classes

Thermal Class	Maximum Time (min)	Maximum Temperature (°C)	Maximum Heat Flux (kW/m^2)
I	25	100	1
II	15	160	2
III	5	260	10
IV	≤1	≥260	≥10

A more appropriate method of characterizing the thermal environment is the thermal operating conditions outlined by Utech [23]. Utech uses the temperature at the firefighter's height as an approximation of the convective heat transfer to the firefighter's gear and the incident heat flux as an approximation of the radiative heat transfer to the firefighter's gear from the surfaces of the room, the upper gas layer, and the fire itself. He combines these two quantities to define three fields of thermal conditions: Routine, Ordinary, and Emergency. According to Utech, routine conditions are defined as those where the surrounding temperature is between 20°C and 70°C with an incident heat flux between 1 and 2 kW/m^2. He maintains that these conditions translate approximately to ambient conditions, not necessarily requiring any thermal protection. As the heat flux and surrounding temperature both increase, the thermal environment crosses into the ordinary operating range. This ordinary range is defined between 70 and 200°C and between 2 and 12 kW/m^2. Ordinary operating conditions represent more serious fire conditions, such as those next to a flashed over room. According to Utech, firefighters would be able to function under ordinary operating conditions from 10-20 minutes at a time, or in other words for the working duration of an SCBA cylinder. Utech considers ordinary operating conditions those that were typical of a house fire. The final classification is emergency operating conditions, which are those thermal conditions exceeding 12 kW/m^2 and 200°C. These operating conditions are intended to be consistent with an environment dangerous to a firefighter in PPE, such as a firefighter trapped in a room that is flashing over. Utech describes this zone as one in which a firefighter's PPE would only be able to withstand an exposure on the order of a few seconds in the emergency operating range. Figure 2.1 offers a visual chart of the thermal operating classes, where the x-axis is heat flux, plotted on a logarithmic scale, in kW/m^2, and the y-axis is temperature, also plotted on a logarithmic scale, in °C.

Rather than representing the threat to electronic equipment, as the NIST thermal classes are intended to do, Utech's thermal operating classes estimate the po-

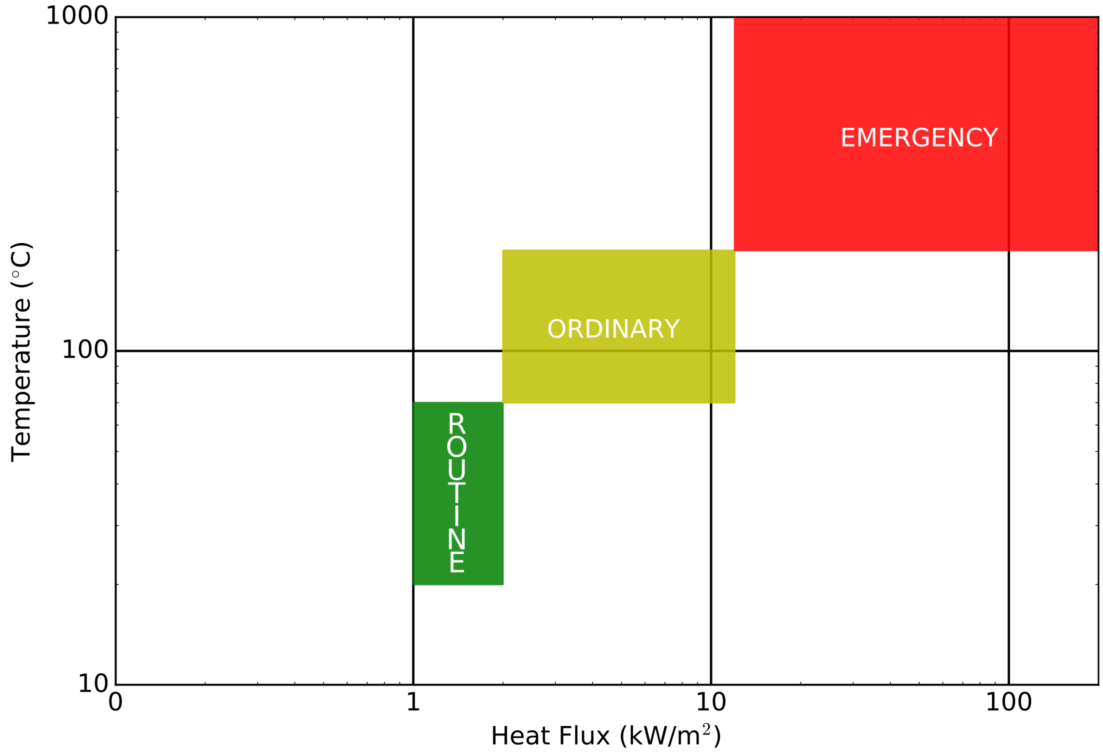


Figure 2.1: Utech's Thermal Exposure Conditions

tential for thermal injury to a firefighter. Utech defined the three operating classes using the results of experiments that had been conducted on contemporary firefighter PPE. The state of the art in firefighter protective equipment has improved significantly since 1973. Modern turnout gear features full encapsulation, with a battery of standard tests which establish minimum performance criteria [24, 25]. Mensch et al. [26] conducted an investigation to quantify the performance of firefighter SCBA facepiece lens under radiant heat flux. The study indicated that the mean temperature of crack formation (180°C) and hole formation (270°C) approximately corresponded to the glass transition temperature and melting point, respectively, of polycarbonate. Further, hole formation was noted at heat fluxes as low as 8 kW/m^2. As the incident heat flux was increased, the time to hole formation decreased. Figure 2.2 shows these benchmarks, as well as the 80 kW/m^2 heat flux that protective ensembles are exposed to during the thermal performance test [24], superimposed on Utech's thermal classes.

Comparison of Figures 2.1 and 2.2 show that the temperature threshold between the ordinary and emergency operating classes approximately is between the temperature that would cause cracking and the temperature that would cause holes to form in SCBA facepieces. Similarly, the threshold between these two operating classes falls between 8 and 15 kW/m^2, which is the range in which hole formation would occur to an SCBA facepiece in several minutes. Thus, the thresholds in Utech's operating classes are representative of thermal conditions which would precipitate the failure of firefighters' PPE. In Utech's chart, there are several areas, such as the areas above and to the right of the ordinary operating class, which do not explicitly fall into any of the three thermal classes. These gaps in the exposure chart are a limitation of Utech's method because, although they do not have a specific hazard classification, such exposures can be hazardous if they exceed the temperature or heat flux criteria presented in Figure 2.2.

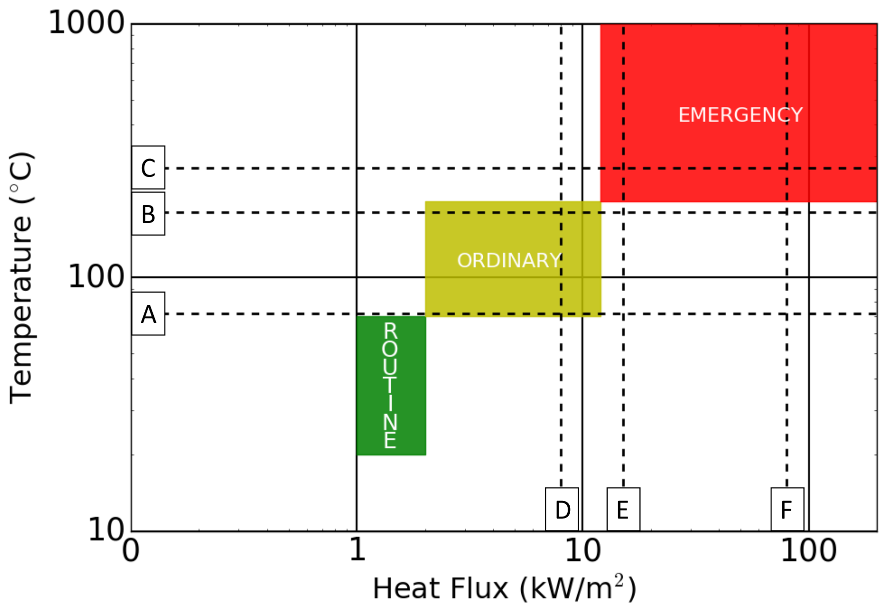


Figure 2.2: Modern PPE Performance Comparison with Utech Thermal Classes

A	72°C (Temperature at which skin is instantly destroyed [27])
B	180°C (Mean temperature of hole formation in SCBA facepiece lens [26])
C	270°C (Mean temperature of crack formation in SCBA facepiece lens [26])
D	8 kW/m^2 (Minimum heat flux exposure where lens failure was noted in less than 20 minutes [26])
E	15 kW/m^2 (SCBA facepiece lens failure occurs between 1.5 and 4 minutes [26])
F	80 kW/m^2 (Heat flux which PPE ensemble is exposed to during Thermal Performance Test (TPP) [24])

Chapter 3: Experimental Approach

This chapter will describe the fuel loads and ventilation configurations that were used in the four heat release rate experiments and the eight concrete burn building experiments. Additionally, the burn structure that was used for the concrete burn building experiments is detailed, and the instruments that were used to conduct each of the tests will be specified.

3.1 Structure

The concrete training building that was used for these experiments was located at the Delaware County Emergency Services Training Center in Sharon Hill, PA. The three-story structure has a footprint of 33.5 ft. x 28 ft, and is shown in Figure 3.1. All of the fires were ignited on the second floor in the designated burn room, labeled Room 201, which was located in the southwest corner of the burn building. Three other rooms on the second floor of the building, labeled 202, 203, and 204, were also instrumented. The remaining 2 rooms on the second floor was sealed from the rest of the space by a cement board barrier, and was used to stage and store fuel. Room 201 had 96 in. ceilings, and measured 224 in. x 152 in. Rooms 202, 203, and 204 had 133 in. ceilings. Room 202 measured 129 in. x 206 in., Room

203 measured 99 in. x 206 in., and Room 204 measured 131 in. x 175 in. The floor plan for the second floor of the training building is shown in Figure 3.2. Figure 3.2 additionally lists the doorways and windows in the burn structure. The dimensions of these openings are given in Table 3.1.

Figure 3.1: Concrete Burn Structure

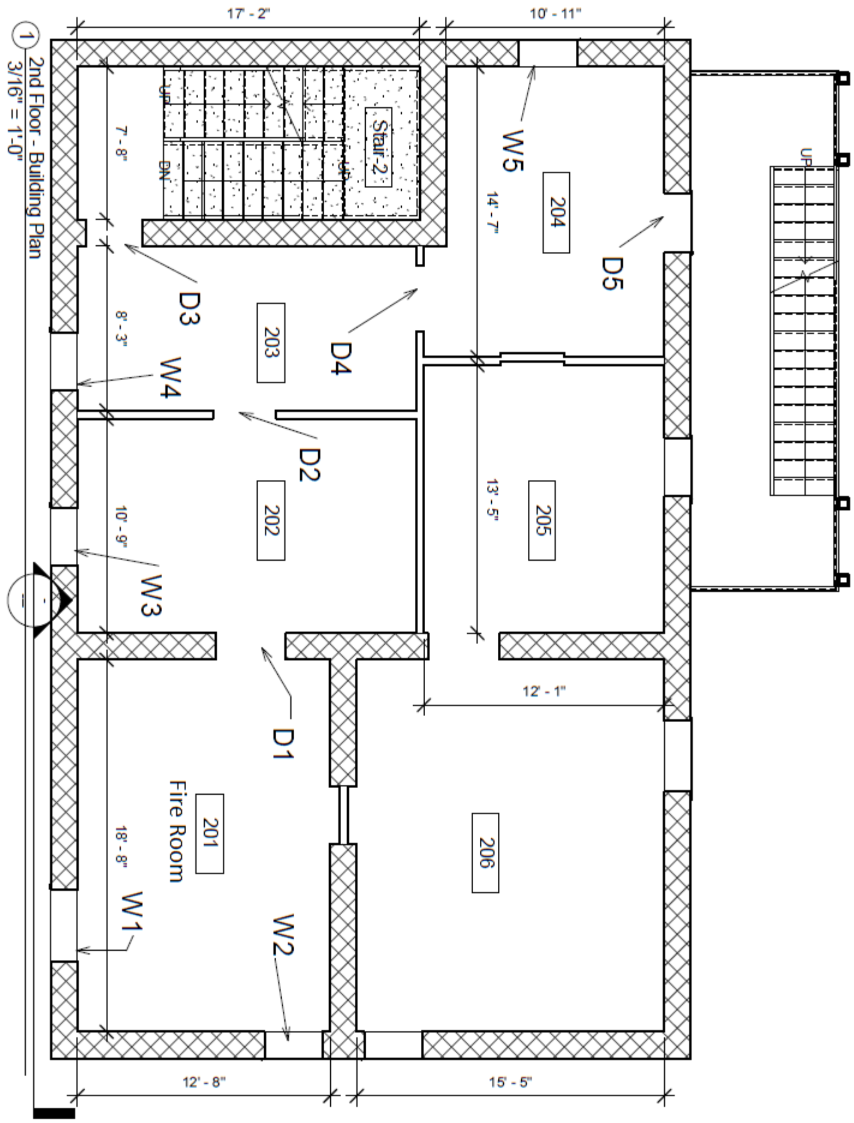


Figure 3.2: Second Floor Layout

Table 3.1: Door and Window Dimensions

Item	Height (inches)	Width (inches)
D1	78.25	40.25
D2	85.5	38
D3	83.5	34.75
D4	86.25	35.25
D5	82.25	28
Front Door (Ground Level)	84.5	34.25
W1	40.5	42.75
W2	40.25	35.25
W3	52.25	47
W4	52.0	47
W5	52.0	47

As Figure 3.2 shows, the second floor is connected to the first and third floors by an interior staircase and an exterior fire escape. The door between Room 204 and the fire escape was not opened in any of these tests, but the exterior door at the base of the staircase was used in the remote ventilation configuration. Other ventilation openings included the windows in Rooms 201, 202, 203, and 204. Room 201 had two of these windows, although only one of these windows was opened during any of the experiments. Additionally, several of the room featured scuppers, which are built-in openings along the floor of the rooms which are used to facilitate drainage and cleanup following a training evolution. An example of one of these scuppers is shown in Figure 3.3. Four such scuppers were on the second floor of the building. Room 204 had a scupper that measured 16.5 inches long by 8 inches high. Rooms

201, 202, and 203 each had a square 8 inch by 8 inch scupper. On the ground floor, there was a four circular scuppers which were 5 inches in diameter.

Figure 3.3: Scupper

3.2 Fuel Packages

Three fuel packages were chosen for the concrete burn building experiments. Two of these fuel loads, the pallets and straw package and the pallets, straw, and OSB package were chosen to be representative of training fuels that are commonly used in the fire service. The third fuel load included sofas, chairs, coffee tables, and end tables, all of which are common furnishings that would be found in a modern home. The intent was to compare the fire dynamics produced as a result of the two training fires to those observed in the furnished room fire. Additionally, the fire dynamics of the furnished room fire can be compared to fire dynamics research that previously has been conducted in residential structures.

3.2.1 Pallets and Straw

Wooden pallets and straw are fuels that are widely used training fuels in the United States. They are appealing to use for live-fire training because of their low cost, high availability, and relative predictability when it comes to fire dynamics. In addition, the ease of ignition and quick cleanup facilitate quick turnover between evolutions, a quality that is quite important to fire instructors aiming to maximize the amount of live fire evolutions possible during a class.

In an effort to ensure that the pallets used as fuel in these experiments were uniform, they were purchased from the same lot. The pallets were weighed in each experiment except for Experiment 3. The total list of pallet weights can be found in Appendix A. The pallets had an average weight of 18.2±1.5 kg. Three such pallets and one bale of straw were used for each test. The average weight of the straw was 14.3±0.5 kg. The total weight of the pallets used in the pallets and straw experiments was 54.8±2.1 kg.The pallets were oriented in a pyramid configuration on top of a steel stand. The steel stand, shown in Figure 3.5, consisted of four steel legs supporting a frame, across which was laid a flattened, perforated steel sheet, which allowed air entrainment into the bottom of the pallet assembly. The bulk of the straw was used to fill the center of the pallet pyramid, and the remainder of the bale was placed beneath the stand and into the slats of the pallets. The entire assembly is shown in Figure 3.4.

Figure 3.4: Pallets and Straw Fuel Package

3.2.2 Pallets, Straw, and OSB

Oriented Strand Board (OSB) is a type of engineered lumber composed of small wood chips pressed together and bonded with some type of resin. Some fire academies and fire training organizations have begun to incorporate OSB, as well as other types of engineered lumber into their live fire training burns. OSB has been identified as having a higher heat release rate than pure wood products, and

Figure 3.5: Training Fuel Stand

therefore has attracted some fire service trainers hoping to create more realistic training environments. In some training evolutions, the OSB is the only fuel that is used, while in others it is used in conjunction with conventional wood-based training fuels, such as pallets and straw. In the OSB tests in this series of experiments, the latter case was studied.

For ease of description, the experiments using pallets, straw, and OSB as a fuel will be referenced simply as "OSB" experiments. The pallets were the same as those used in the pallets and straw experiments. Three pallets with a average weight of 18.2±1.5 kg and one bale of straw were used for each experiment. The total list of pallet weights can be found in Appendix AThe average weight of the straw was 14.3±0.5 kg. The OSB sheets were 7/16 in. thick 4 ft. x 8 ft. sheets. The OSB sheets were weighed together, with a total weight of 42.2 kg. the approximate total weight of the pallets, straw, and OSB fuel package is 155.7 kg. The pallets and straw were configured in an identical way to that described in the previous section. The OSB sheets were placed behind the pallet pyramid, along the rear wall of the fire room. The pallets, straw, and OSB assembly is depicted Figure 3.6

Figure 3.6: Pallets, Straw, and OSB Fuel Package

3.2.3 Furniture

The furnished room fire consisted of two couches, two chairs, two end tables, two lamps, a coffee table, carpet, and carpet padding. The furniture was selected to simulate the living room of a modern home. The couches and chairs were purchased from a retailer and were assembled prior to the experiments. The upholstery was primarily polyurethane foam and the frame of the couches was wooden. The chairs had a polyurethane foam cushion and an expanded polystyrene frame. The end table and coffee table were made of pressboard. The weights of each of the respective pieces of the fuel package are given in Figure 3.2. The combined weight of the The layout of the furnished room is shown in Figure 3.7. furnished room fuel package is approximately 210.5 kg.

Figure 3.7: Furniture Layout

Table 3.2: Furnished Room Contents

Furniture Item	Quantity	Weight (kg)
Couch	2	46.0
Chair	2	7.6
End Table	2	15.4
Coffee Table	2	20.6
Carpet	1	15.8
Carpet Padding	1	10.9
Lamp	2	2.3

3.3 HRR Characterization Tests

To evaluate the heat release rate characteristics of each of the fuel packages described above, a series of tests were performed in UL's oxygen consumption calorimetry laboratory. Each fuel package was arranged in a manner identical to the configuration in the concrete burns structure, but instead of the concrete burn room, a 144 inch x 144 inch compartment was constructed. The compartment was framed with dimensional lumber and had an interior finish of gypsum board. The room has a 96 inch wide x 80 inch tall doorway, which was chosen to provide ample ventilation to the compartment. Since this ventilation configuration was different than that in the concrete burn building experiment, the heat release rates should be used only to compare the fuels to each other for a similar ventilation opening and room configuration, rather than extrapolating the results to the concrete burn building experiments.

The oxygen consumption calorimeter used for these experiments was located at Underwriters' Laboratories facility in Northbrook, IL. Four heat release rate experiments were performed. One experiment each was performed for the pallets and straw and the OSB fuel packages, and two replicates of the furnished rooms were performed. This was done to characterize the variability of the furnished room fuel package. The calorimeter reported heat release rate in MW at 1 second intervals for the heat release rate experiments. Bryant and Mullholland [28] estimate the uncertainty of oxygen consumption calorimeters measuring high heat release rate fires at ±11%. They identify several sources of error within hte calorimeter, but one of the primary sources is the uncertainty in the gas concentration measurements.

3.3.1 Heat Release Rate Characterization Results

The results of the heat release rate characterization experiments are summarized in Figures 3.8 and 3.9 and Table 3.3. The total energy released was determined by numerically integrating the total heat release rate curve using an Euler scheme, described in Equation 3.1. A 25 second moving average was applied to each of the heat release rate graphs to minimize some of the fluctuations in the raw data.

$$E_{n+1} = E_n + \Delta T * HRR_n \tag{3.1}$$

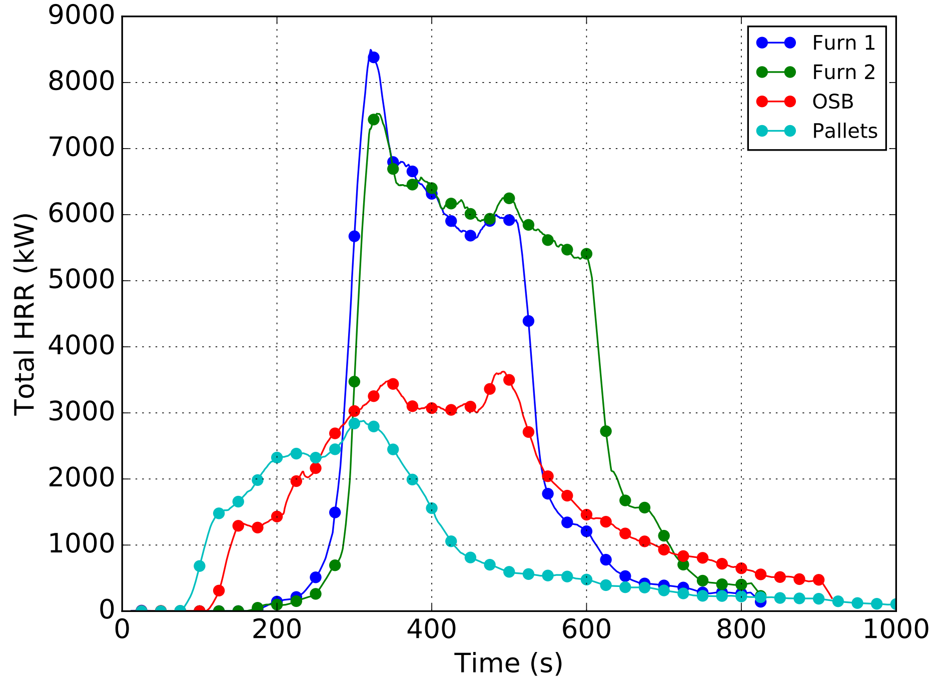


Figure 3.8: Heat Release Rate vs. Time for Heat Release Rate Characterization Experiments.

Table 3.3: Peak HRR and Total Energy Released

Fuel Package	Peak Heat Release Rate (MW)	Total Energy Released (GJ)
Pallets and Straw	2.88	0.95
OSB	3.63	1.44
Furnished Room 1	8.50	1.79
Furnished Room 2	7.52	2.19

The heat release rate of the pallets and straw first began to increase at approximately 50 seconds from the start of the test, and the rate of change of the HRR remained positive until approximately 325 seconds after ignition. The peak slope of

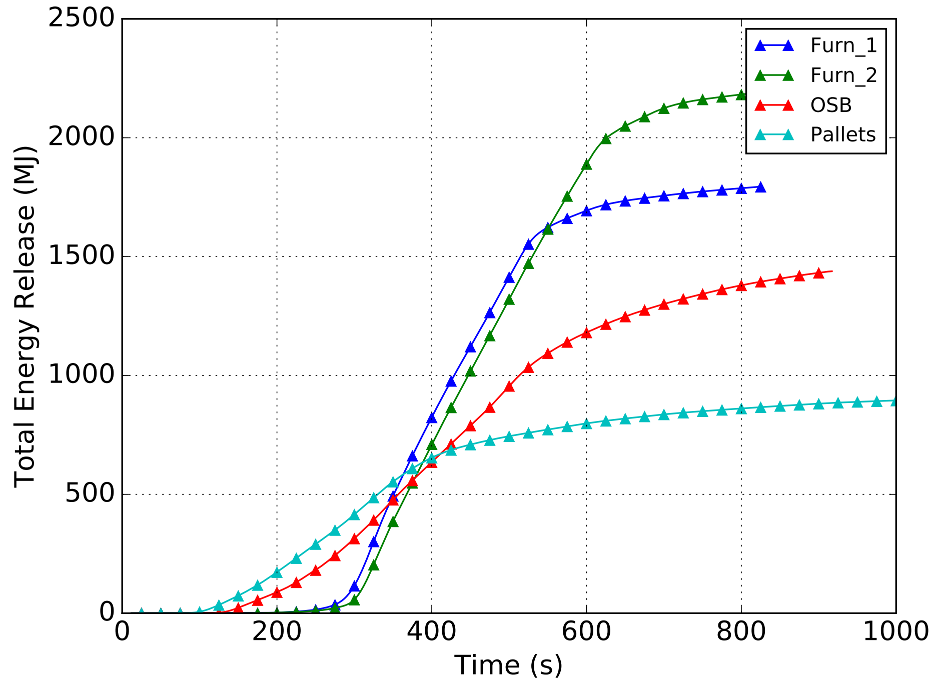


Figure 3.9: Total Energy Released vs. Time for Heat Release Rate Characterization Experiments.

the heat release curve was noted in the period immediately following ignition, where the rate of change of heat release rate was 30 kW/s.

The rate at which the HRR increased in the period leading up to the peak HRR was similar for the OSB fuel package, with a peak slope of approximately 30 kW/s. The heat release rate observed in the OSB fuel package was 26% higher than that noted in the pallets and straw experiment. Perhaps a more singificant difference however, can be seen in Figure 3.9. This figure illustrates that the total energy released by the OSB fuel package is 52% greater than that released by the pallets and straw fuel package. This trend is also manifested in Figure 3.8. In the OSB fuel package, after the peak heat release rate is observed, the heat release rate remains above 3 MW for another 150 seconds before beginning to decrease. In the pallets and straw, on the other hand, the heat release rate began to decrease almost immediately. So, while the peak rate of growth that was observed in the two training fuel packages was similar, the OSB exhibited a higher peak heat release rate. The sustained period of high heat release also resulted in a greater total energy released than the pallets and straw fuel package.

Two replicates of the furnished room fuel packages were performed, each one with identical furnishings and layout. In both tests, the HRR did not begin to increase significantly until after 200 seconds from the beginning of the test. Once this point was reached, however, the rate of increase of the heat release rate was above 150 kW/s, which was approximately 5 times that noted in the training fuels. Both furnished rooms reached their peak heat release rate close to 325 seconds. The peak heat release rate in Furnished Room 1 was 8.50 MW, which was 13% higher than the 7.52 MW peak observed in the second furnished room. After reaching this peak, the heat release rate remained high, which resulted in total energy releases that were higher than both training fuels. The heat release rate rapidly declined after this period. In Furnished Room 1 heat release rates greater than 5.5 MW were observed for approximately 300 seconds. In the second furnished room, heat release rates above 5.5 MW were observed for approximately 400 seconds.

The peak heat release rates between the two furnished room replicates varied by between 11.5% and 13.0%, which is slightly greater than the combined uncertainty of the calorimeter. The difference between total energy released between the two replicates was more significant, with the difference falling between 18% and

22%. This difference can be explained in part by the longer period of sustained heat release rates in the second replicate of the furnished room. This longer period of sustained heat release could because more of the fuel burned in the second replicate than the first, or possibly because of the difference in peak heat release rate behavior between the two, or some combination of both factors. Thus, in addition to exhibiting higher peak heat release rates and total energies released than the OSB or pallets and straw training fuels, the furnished rooms demonstrated a peak rate of change in heat release rate that was nearly 5 times higher than that noted in the training fuels.

3.4 Experiments

A total of eight experiments were conducted. Each experiment combined one of the fuel packages described in the previous section with a ventilation configuration, in an effort to explore the effects of these ventilation configurations on the behavior of the training fire. The three configurations were burnout, remote vent, and near vent. In the burnout case, no doors or windows were opened for the duration of the test. This was done in an effort to examine the fuels without the outside influence of ventilation. In the far vent case, the door on the ground floor was opened in conjunction with the window in Room 204. This was intended to examine the effect of a ventilation point far from the seat of the fire, creating a flow path where the inlet was the front door and the exhaust was the far window. The two vent points for this configuration are shown in Figure 3.10. The near vent case was intended to examine the effect of ventilation close to the fire. In this case, the Room 201 window was opened, shown in Figure 3.11.

(a) Front Door **(b)** Room 204 Window

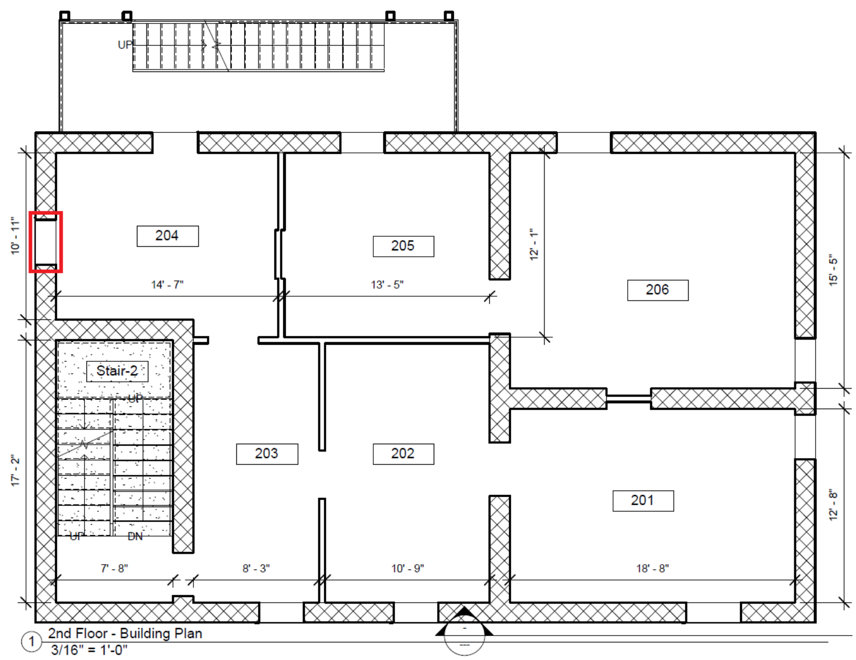


Figure 3.10: Far Ventilation Case

Table 3.4 lists the experiments that were performed, the fuel package, the ventilation configuration, and the time at which ventilation was performed. Ventilation times were determined by monitoring the oxygen concentrations at the 2 foot and 6

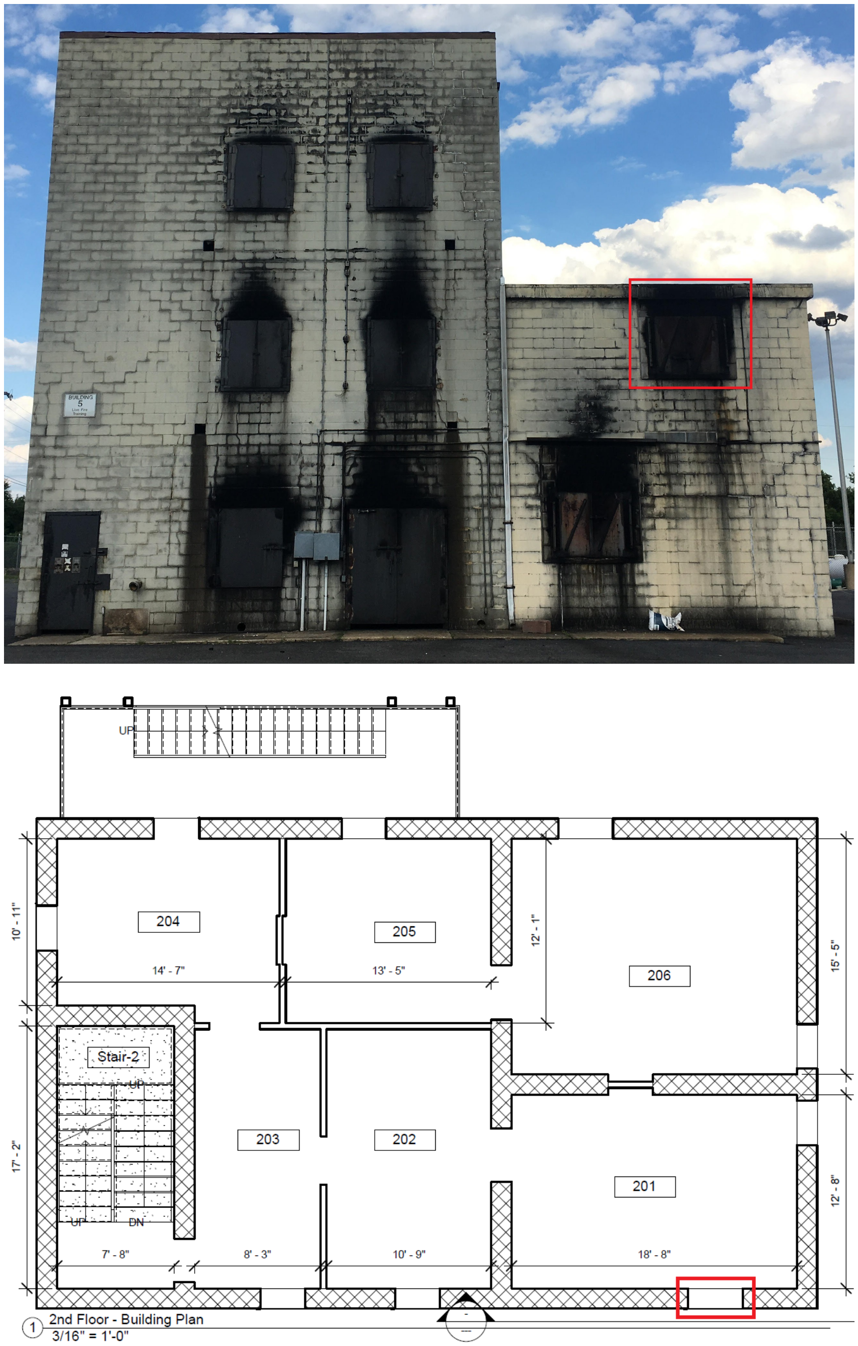


Figure 3.11: Near Ventilation Case

foot levels, and performing ventilation when the concentrations reached a minimum value. It should be noted that a no ventilation experiment was not performed for the OSB fuel package. This was done because of the time constraints that were required for this test series, which were not conducive to an additional experiment. While a no ventilation case for the OSB fuel package would indeed be useful, it was assumed that the fire dynamics of the OSB would be bounded by the pallets and straw and the furniture.

Table 3.4: Experiment Matrix

Experiment	Fuel	Vent Scenario	Vent Time (s)
Experiment 1	Furniture	Near Vent	420
Experiment 2	Furniture	No Vent	-
Experiment 3	Pallets and Straw	Remote Vent	239
Experiment 4	OSB	Remote Vent	299
Experiment 5	Furniture	Remote Vent	511
Experiment 6	Pallets and Straw	No Vent	-
Experiment 7	Pallets and Straw	Near Vent	480
Experiment 8	OSB	Near Vent	247

3.5 Instrumentation

This section detailes the equipment that was used in the concrete training building experiments. These instruments were used to monitor the temperatures, heat fluxes, gas velocities, and oxygen concentrations throughout the structure. The layout of these instruments is given in Figure 3.12.

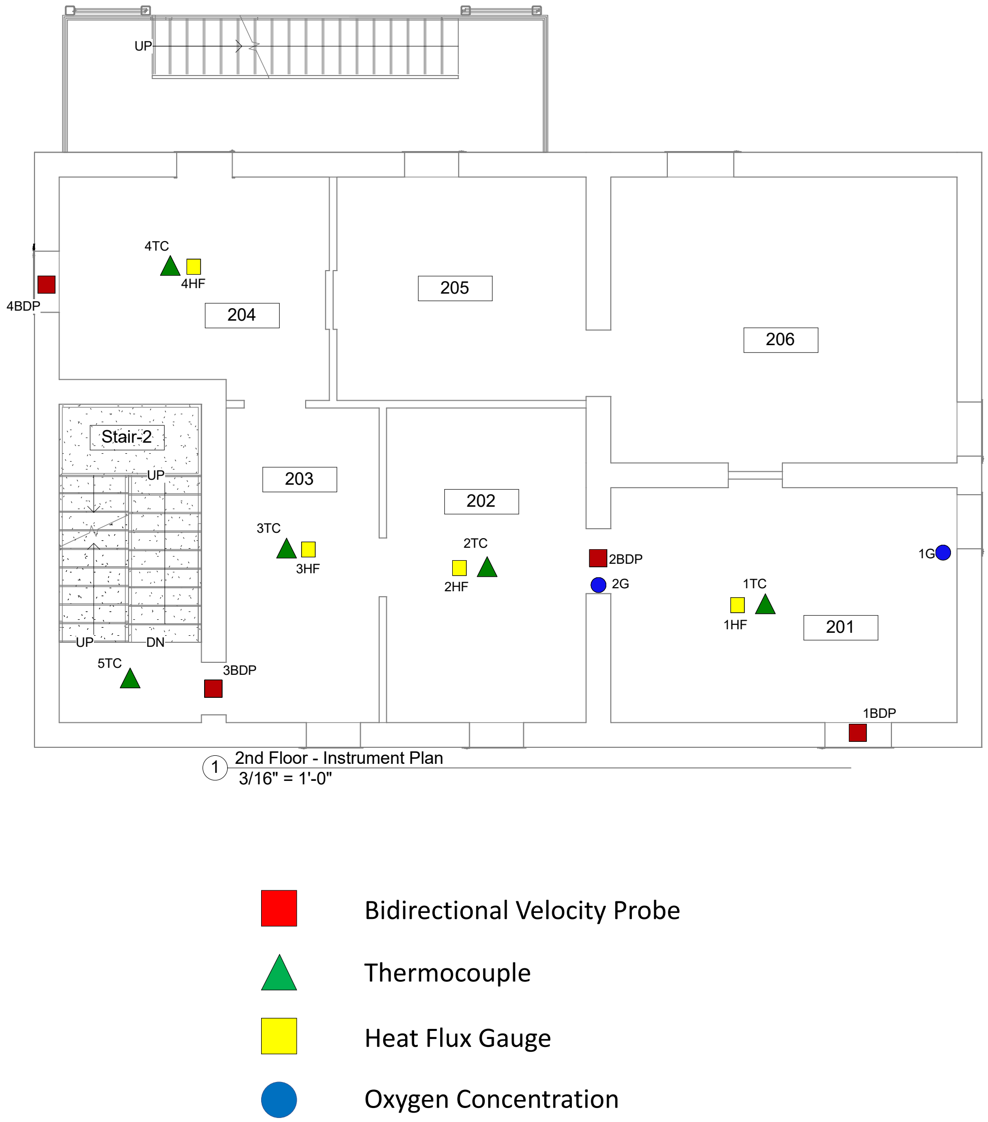


Figure 3.12: Instrument Locations

3.5.1 Thermocouple

The thermocouples used in these experiments were chromel-alumel, Type K thermocouples, The thermocouple wire was manufactured by Omega Engineering, and has a nominal 0.5 mm diameter. The individual thermocouple wires were arranged into "trees," which spaced thermocouples at 1 foot increments from the floor to the ceiling of each rooms. In Room 201, the trees had 7 thermocouples and in Rooms 202, 203, and 204, the trees had 12 thermocouples. The locations of these thermocouple trees are denoted by green triangles in Figure 3.12

According to Omega, the uncertainty of the thermocouple wire is 2.2°C for temperatures below 293°C and .75% for temperatures above this range [29] In addition to the built-in uncertainty of the sensor, radiative effects to the thermocouple should be considered. Several studies have studied these effects on thermocouple measurement uncertainty in compartment fires [30,31]. These studies indicated that when the thermocouple is located in the upper gas layer, the temperature of the surrounding gas is typically higher than the measured reading, although this difference is not as pronounced as when the thermocouple is in the lower layer. When the thermocouple is in the lower layer, particularly when the thermocouple is in a fully involved room fire, the percent error in measured temperature can be much larger. Because of these radiative contributions, the expanded uncertainty is estimated as 15%.

3.5.2 Heat Flux Gauge

Heat flux was measured using a nominal 2.54 cm diameter, water-cooled, Schmidt-Boelter heat flux gauge. These gauges were mounted in metal ammunition cans, which were also water cooled and insulated. These protective cans allowed the heat flux gauges to be placed close to the fire room without being damaged or destroyed. The heat flux gauges were oriented towards the ceiling in an effort to evaluate the heat flux from the hot gas layer in the room. It should be noted that these gauges are total heat flux gauges, and therefore capture both convective and radiative heat transfer. The radiative heat transfer is largely a function of the temperature of the hot gas layer, while the convective heat transfer is dependent both on the ambient temperature and the velocity of the gas flow. The locations of the heat flux gauges are shown by yellow squares in Figure 3.12.

The manufacturer of these heat flux gauges lists the uncertainty as 3%. Each gauge has a unique calibration curve, which converts the voltage signal into a heat flux. Such gauges are NIST-traceable, and must be re-calibrated from time to time to ensure accuracy. A study on the uncertainty of measurements for heat flux gauges lists the maximum uncertainty for these instruments as 8% [32].

3.5.3 Bidirectional Velocity Probes

Gas velocity measurements were conducted using a differential pressure transducer coupled with a thermocouple measurement. The differential pressure measurement was conducted using a stainless steel probe, the two ends of which were connected to a Setra Model 264 differential pressure transducer with a 1.0 inch water column (248.8 Pa) range. Five of these probes constituted each array. The arrays were located in the window to Room 201, the doorway between Rooms 201 and 202, the stairwell doorway, and the window in Room 204. In each case, the array was centered laterally in the door. The vertical probe spacings for each of the arrays are listed in Table 3.5. The thermocouple was a 0.62 inch type KSL iconel 600 sheathed ground junction thermocouple with a 24 gauge Type K lead. The locations of the bidirectional probe arrays are shown by red squares in Figure 3.12. The expanded uncertainty of the bidirectional probe velocity measurements is 5% [33].

Table 3.5: Bidirectional Probe Spacings

Array	**Location**	**Probe Spacings (inches)**
1BDP	Room 201 Window	6.75, 13.5, 20.25, 27, 33.75 (from bottom ledge)
2BDP	Room 201/202 Door	13, 26, 39, 52, 65 (from floor)
3BDP	Stairwell Door	14, 28, 42, 56, 70 (from floor)
4BDP	Room 204 Window	8.5, 17, 25.5, 34, 42.5 (from bottom ledge)

3.5.4 Gas Analyzers

Gas samples were collected at heights of 2 feet and 6 feet from the floor in two locations in Room 201, shown by blue circles in Figure 3.12. The samples were collected by stainless steel tubes, which were run into the fire room. The samples were first passed through a coarse paper filter (Solberg Model 8242) before being passed through a condensing trap to remove moisture. The samples then ran through a nominal 0.75 CFM pump (Cole Palmer Model L-79200-30), and from there through a drying tube (Perma Pure Model FF-250-SG-2.5G) and a fine filter (FF-250-E-2.5G) before finally running to the OxyMat6 Siemens Gas Analyzers.

The range for the oxygen measurements in the OxyMat6 are from 0-25%. The listed measurement uncertainty under ambient conditions for this operating range is 0.32% by volume. This uncertainty would be expected to further increase under fire conditions, as evaluated by Axelsson et al. in a study aiming to quantify the uncertainty in the oxygen concentration measurement during oxygen consumption calorimetry tests [34]. The results of the uncertainty analysis indicated that the combined uncertainty of the oxygen concentrations measurement at 18% oxygen, measured curing an approximately 1 MW fire test, was 0.65%.

Chapter 4: Experimental Results

This chapter presents the measurements from the concrete burn building experiments described in the previous chapter. Because of time constraints, several experiments had to be conducted in the same day. The experiments were planned so that the experiments in which the most severe thermal conditions were anticipated were conducted at the end of the day. Table 4.1 lists the intial temperatures, taken as an average across the height of the fire room, the order in which the test was conducted that day, the time since the previous test, and the ambient temperature.

Table 4.1: Initial Temperatures

Experiment	Test of day	Time Since Previous Test (hours)	Average Initial Temperature °C °C	Ambient Temperature °C
Experiment 1	4	3	42±4	32
Experiment 2	2	3	32±4	33
Experiment 3	3	2	39±4	29
Experiment 4	1	-	33±1	33
Experiment 5	2	6	34±3	29
Experiment 6	1	-	32±1	32
Experiment 7	2	2	40±4	34
Experiment 8	3	2	43±5	36

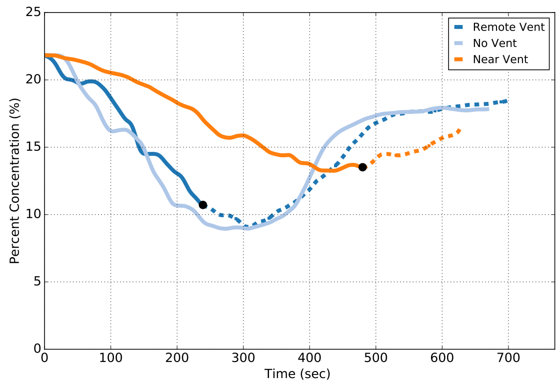
Table 4.1 shows that tests that were conducted later in the day showed a higher initial temperature and a higher standard deviation from the average than test which were conducted in the morning. This can be attributed to the nature of the concrete burn building, which has a tendency to hold heat after training evolutions. Since at least two hours were allowed between experiments, these temperature differences are only on the order of a few degrees with a maximum difference of 7°C between the start and end of a testing day. Thus, it is not expected that the changes had a substantial effect on the experimental results, although previous studies have emphasized the importance of alotting for sufficient time between evolutions [18].

One of the considerations of this study is the effect that ventilation, or the absence of ventilation, has on fire behavior, the oxygen measurements in the fire room are first presented for each of the experiments. Then, the heat flux and temperature results are presented for each of the three fuel packages. The 7 foot temperature measurements used to characterize the response to fire, as the temperature at this level would be the first to respond to changes in fire growth. The 3 foot temperature measurements are presented to represent the temperature that a crawling firefighter would be exposed. The results focus on the measurements that were conducted in the fire room. Peak heat fluxes and temperatures in the remote rooms are presented in the Appendix A.

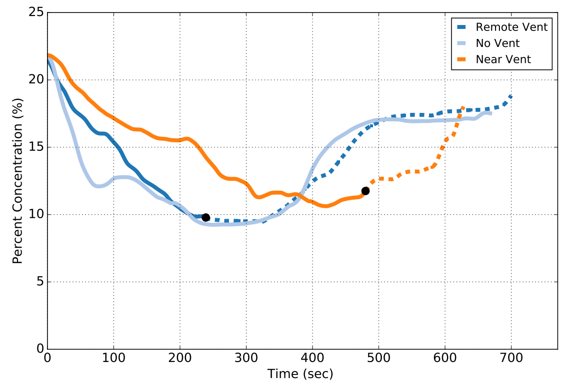
4.1 Room 201 Oxygen Concentrations

The oxygen concentration was measured in 4 locations, each of them in the fire room. Two separate two-sensor arrays, one located at the door between Room 201 and Room 202, and the other located in the corner on the opposite wall, each had sensors at 2 ft. and 6 ft. from the floor. The intent of the different heights is to offer an approximation of the oxygen concentration within the thermal layer itself (6 ft.) and at a lower elevation in the room, where fresh air has the ability to be entrained. The oxygen concentrations can be considered in two time frames: pre-ventilation and post-ventilation. Figures 4.1, 4.2, and 4.3 show the oxygen concentration profiles with respect to time for the pallets and straw experiments, the OSB experiments, and the furniture experiments, respectively. In these plots, the black dots represent the point at which ventilation was performed. The solid lines represent the pre-ventilation period and the dotted lines represent the post-ventilation period.

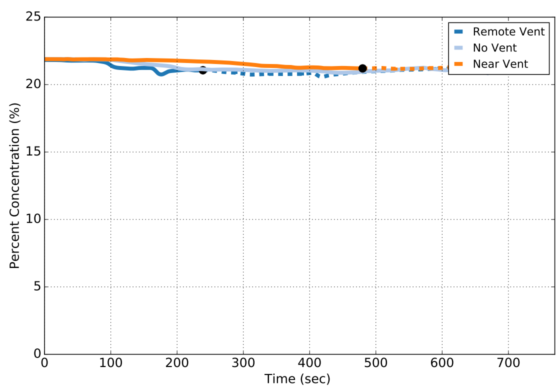
4.1.1 Pallets and Straw Oxygen Concentrations



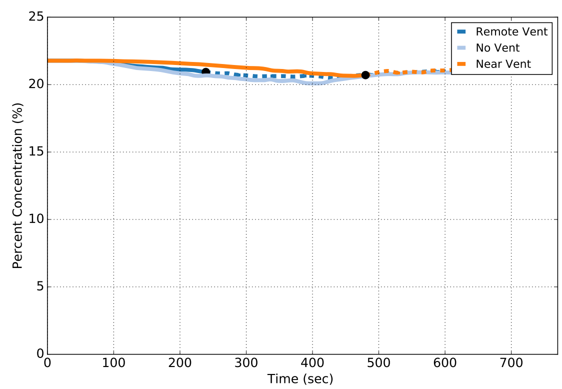
(a) Rear 6 ft.



(b) Doorway 6 ft.



(c) Rear 2 ft.



(d) Doorway 2 ft.

Figure 4.1: Oxygen Concentration in Room 201 for Pallets and Straw Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

Table 4.2: Room 201 6 ft. O_2 Concentrations for Pallets and Straw Experiments

Experiment	Minimum Pre-Vent O_2 %		O_2 % at Ventilation	
	Rear	Doorway	Rear	Doorway
3 (Remote Vent)	10.7	9.8	10.7	9.8
6 (No Vent)	9.0	9.2	-	-
7 (Near Vent)	13.3	10.6	13.5	11.8

In Experiments 3, 6, and 7, as the fire developed, the oxygen concentrations at the 6 ft. level decreased, as seen in Figures 4.1a and 4.1b. In Experiment 3, the remote ventilation case, the oxygen concentration decreased to between 9 and 10 %, at which point the door and Room 204 window were ventilated. At this point, the O_2 concentration measured at the doorway gas analyzer is approximately constant at 9.8%. The sensor in the rear of the room measures 10.71%, and is continuing to decrease. Both of these trends continue for a brief period of time after ventilation, before starting to increase. By the end of the experiment, the O_2 concentration at the 6 ft. level was above 17.5% in both the doorway and the rear of the room. The minimum 6 ft. oxygen concentrations and the 6 ft. concentrations at the time of ventilation for Experiment 3, as well as the rest of the pallets and straw experiments, are listed in Table 4.2.

A similar trend was noted in Experiment 7. The rate of decrease of oxygen concentration was slower in this test than in Experiment 7, only reaching 10.6 % at the doorway and 13.3 % in the rear of the fire room before reaching a steady state and briefly starting to increase, at which point ventilation was initiated. In contrast to Experiment 3, the oxygen concentrations reached their minimum level prior to ventilation in Experiment 7. The 6 ft. oxygen concentrations began to increase more quickly than was noted in Experiment 3, increasing from 13.5% to 18.2% in the rear of the room and from 11.6% to 13.5% by the end of the test.

In the no ventilation case, Experiment 6, the oxygen concentration decreased at a rate similar to Experiment 3. It reached a minimum concentration close to 9%, before beginning to increase. The rate of increase in oxygen concentration was rapid at first, eventually decreasing and reaching a steady state near 18.6% in the rear and 19.1% in the doorway. Thus, in the pallets and straw experiments, the initial growth of the fire and development of a thermal layer resulted in a decrease in oxygen concentrations.

In each of the experiments, this oxygen concentration returned to concentrations close to 18% by the end of the test, regardless of whether ventilation was performed. The decreased oxygen profile indicates an increase in combustion products, such as soot, carbon monoxide, and carbon dioxide, in the thermal layer during fire growth, and that, as the growth rate decreased, the concentration of oxygen began to increase as the smoke and other gases was exhausted from the structure, whether through ventilation openings such as windows or doors, or through openings in the building itself, such as scuppers or gaps.

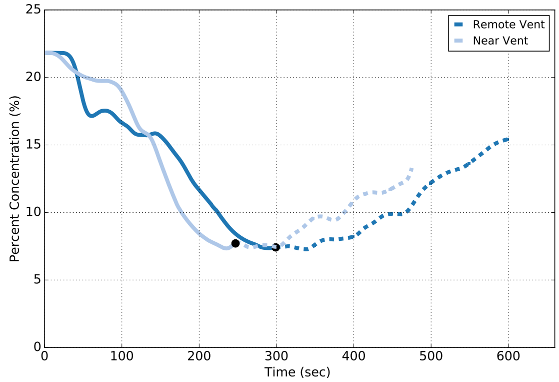
The marked decrease in oxygen concentration that was observed at the 6 ft. level was not noticed in the 2 ft. gas analyzer locations. Figures 4.1c and 4.1d show the 2 ft. oxygen concentration profiles for Experiments 3, 6, and 7. Inspection of the plots reveals that the oxygen concentrations at the 2 ft. level do not fall below 20%

for the entire duration of the test. While the oxygen concentrations do decrease, it is not nearly on the same order of magnitude as the decrease noted at the 6 ft. sensors. This indicates that two distinct zones exist in the pallets and straw experiments: a layer close to the floor that is mostly comprised of air being entrained into the structure, and a hot gas layer that is oxygen deficient. The presence of these two distinct layers indicates that the rate of combustion of smoke and other combustion products is less than the rate at which these products of combustion are exhausted through leakage in the structure.

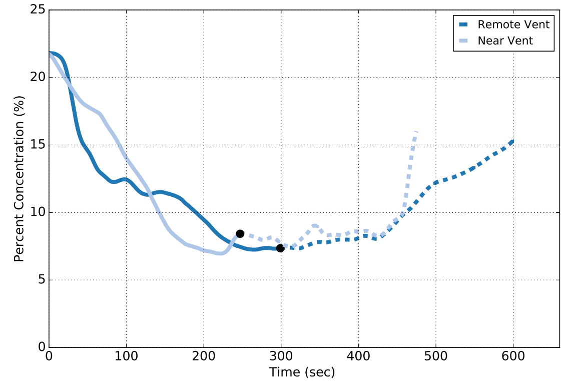
Comparison of the oxygen concentrations, particularly at the 6 foot level, between Experiments 3 and 6, which were the remote ventilation and no ventilation cases, respectively, reveals that the rate of oxygen depletion and subsequent recovery followed a similar trend, despite the ventilation that occurred in Experiment 3. This, coupled with the negligible change in oxygen concentrations at the 2 foot level in each of the three experiments, would indicate that ventialtion did not have a significant impact on the growth of the pallets and straw fires.

4.1.2 OSB Oxygen Concentrations

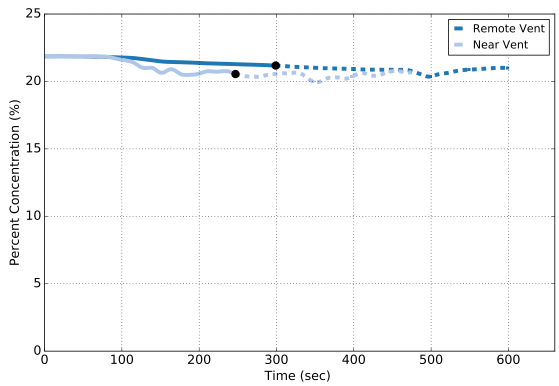
The experiments using OSB as a fuel, Experiments 4 and 8, displayed quite similar pre-ventilation 6 ft. oxygen depletion following ignition. The 6 ft. oxygen concentrations began to decline shortly after, reaching minimum values below 7.4%, as listed in Table 4.3. In both of the experiments, the oxygen concentrations began to increase following this minimum value. After ventilation, there was a brief period



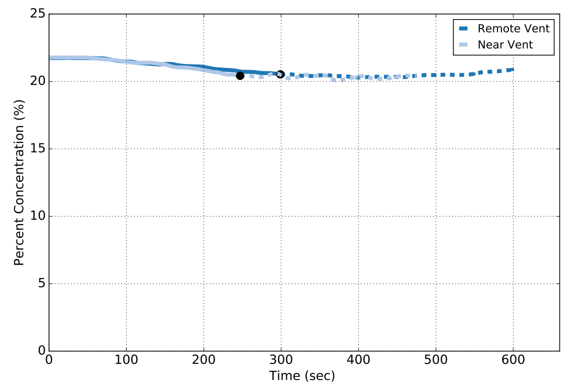
(a) Rear 6 ft.



(b) Doorway 6 ft.



(c) Rear 2 ft.



(d) Doorway 2 ft.

Figure 4.2: Oxygen Concentration in Room 201 for OSB Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

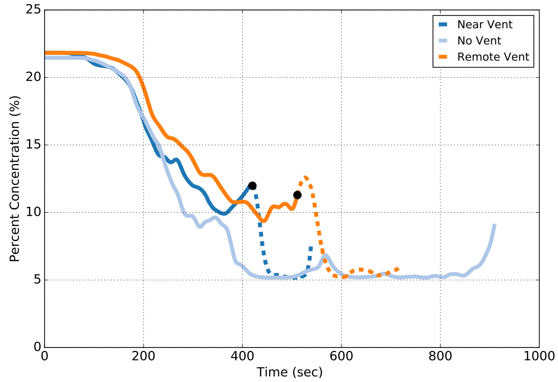
where the oxygen concentration remained approximately constant, before the 6 ft. oxygen concentrations began to rebound, reaching values above 16% by the end of the test period. The minimum values observed in Experiments 4 and 8 were lower than the minimum values noted in the pallets and straw training fire experiments. These minimum values occurred within the same 100 second time frame as the min-

Table 4.3: Room 201 6 ft. O_2 Concentrations for OSB Experiments

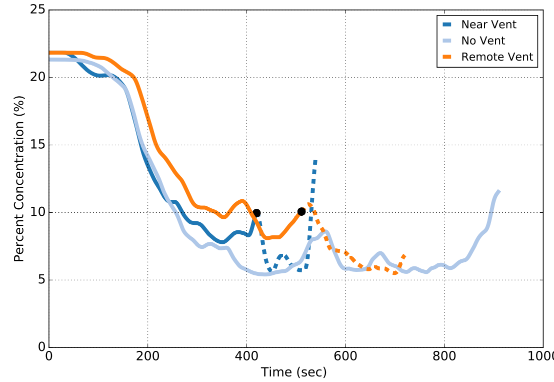
Experiment	Minimum Pre-Vent O_2 %		O_2 % at Ventilation	
	Rear	Doorway	Rear	Doorway
4 (Remote Vent)	7.4	7.3	7.4	7.4
8 (Near Vent)	7.3	7.0	7.7	8.4

imum values in Experiments 3 and 6, while the pallets and straw fire in Experiment 7 took considerably longer to reach a minimum value.

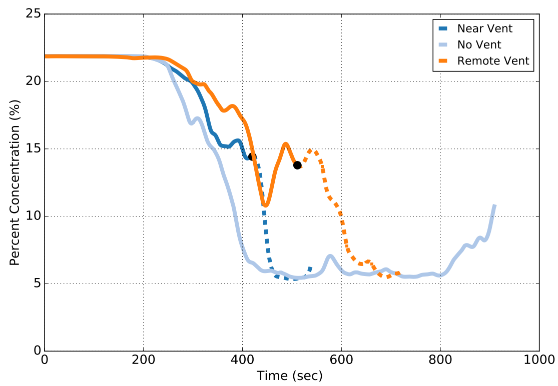
The trend in 2 ft. oxygen concentrations for the OSB experiments was similar to the pattern in the pallets and straw tests, staying above 20% for the duration of the experiment. Just as in the pallets and straw tests, this indicates that two distinct layers exist in the fire room: a fresh air layer close to the floor, where oxygen concentrations remain close to ambient levels, and an oxygen deficient gas layer close to the ceiling. In the absence of additional ventilation, the leakage through the concrete building is sufficient to maintain these close-to-ambient oxygen concentrations in the lower layer, while the upper layer remains oxygen-deficient. When additional ventilation is provided, the fire is not producing combustion products at a rate that is sufficiently high to overcome the ventilation openings, and the oxygen concentration in the upper layer increases.



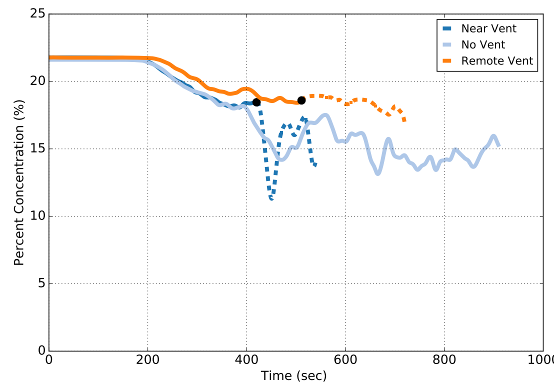
(a) Rear 6 ft.



(b) Doorway 6 ft.



(c) Rear 2 ft.



(d) Doorway 2 ft.

Figure 4.3: Oxygen Concentration in Room 201 for Furnished Room Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

4.1.3 Furnished Room Oxygen Concentrations

The most profound changes in ventilation were noted in the furnished room experiments (1, 2, and 5). The oxygen concentration profiles for these tests are shown in Figure 4.3. The oxygen concentrations remain close to ambient levels for

Table 4.4: Room 201 6 ft. O_2 Concentrations for Furnished Room Experiments

Experiment	Minimum Pre-Vent O_2 %		O_2 % at Ventilation	
	Rear	Doorway	Rear	Doorway
1 (Near Vent)	9.9	7.8	12.0	10.0
2 (No Vent)	5.2	5.4	-	-
5 (Remote Vent)	9.4	8.1	11.3	10.1

Table 4.5: Room 201 2 ft. O_2 Concentrations for Furnished Room Experiments

Experiment	Minimum Pre-Vent O_2 %		O_2 % at Ventilation	
	Rear	Doorway	Rear	Doorway
1 (Near Vent)	14.3	18.1	14.4	18.5
2 (No Vent)	5.4	13.1	-	-
5 (Remote Vent)	10.8	18.4	13.8	18.6

a longer period of time than in the training fire tests, a trend which is consistent with the delayed growth observed in the HRR experiments. In the no ventilation test in Experiment 2, the oxygen concentrations at both 6 ft. sample points and the 2 ft. sample point in the rear of the fire room all reached a minimum between 5% and 5.5%, as shown in Tables 4.4 and 4.5. The 2 ft. oxygen concentration in the doorway was considerably higher, remaining above 13.1% for the duration of the experiment. The oxygen concentration is likely higher at this location because cold air is entering the fire room through the lower half of the doorway. A similar trend was noted in Experiments 1 and 5.

In Experiment 5, oxygen concentrations declined in a manner similar to Experiment 2. in the gas layer, the concentrations declined to 8.1% in the doorway and 9.4% in the doorway. In the rear of the room, at the 2 ft. level, the concentration exhibited a minimum value of 10.8% prior to ventilation. In the doorway, the oxygen concentration remained higher than 18%. After reaching these minimum values, the oxygen concentration at each location began to increase, at which point ventilation was initiated. Oxygen concentrations at each location briefly continued their increase before declining again, reaching values between 5 and 6% at the 6 ft. sensors and in the rear of the fire room. The oxygen concentration in the doorway remained high, only decreasing slightly in the period after ventilation.

The pre-ventilation oxygen concentrations in Experiment 1 followed the same trend as Experiment 5, although the minimum values were reached at earlier times. The minimum oxygen concentrations in the gas layer sample points were 7.8 and 9.9%, and the minimum observed concentration in the rear 2 ft. sample point was 14.3%. As these oxygen concentrations started to increase, ventilation was initiated, which resulted in a rapid decrease in oxygen concentrations at both 6 ft. sample points, as well as the 2 ft. sensor in the rear of the fire room. All of these sensors recorded values between 5 and 6% for the majority of the period following ventilation. The 2 ft. oxygen concentration remained higher than the other locations in the post-ventilation period, reaching a minimum of 11.2%, but exhibiting values above 16% for most of the period.

For the furniture fires, the pre-ventilation behavior involved a decrease in oxygen concentrations at both 6 ft. locations and at the 2 ft. rear location in the period preceding ventilation. In each of the furnished room experiments, the oxygen concentrations at each of these locations fell to between 5 and 6%, even in the non-ventilated case (Experiment 2). This would indicate that in these areas of the room, combustion would not be possible because of the lack of available oxygen. This lack of available oxygen was not noted in the 2 ft. doorway sample location, however. Even in the no ventilation case, where there were no window or door ventilation openings, the oxygen concentrations measured at this location were higher than those in the other three locations. This would indicate that the fire is drawing fresh air into the fire room through natural leakage points within the training building. In the remote ventilation experiment (Experiment 5), the air entrained through leakage was supplemented by air entrained through the first floor door and window. This corresponded with a higher minimum oxygen concentration than was observed than in the other two furniture experiments. Thus, the furnished room tests varied considerably from the training fuels in the respect that these rooms achieved oxygen-deficient conditions close to the floor- a phenomenon that was not observed in the pallets and straw or OSB fires.

4.2 Thermal Conditions

4.2.1 Pallets and Straw Experiment Thermal Conditions

As discussed in the previous section, the oxygen concentration profiles in the pallets and straw experiments exhibited negligible depletion at the 2 foot level, while the behavior of the oxygen concentration with time at the 6 foot level did not appear to be impacted by ventilation in either of the experiments where ventilation was present. The floor heat flux, 3 foot temperature, and 7 foot temperature in these experiments were similarly unaffected by ventilation. The time histories of these three values are shown in Figures 4.4, 4.6, and 4.5. Comparison of the rate of change of these quantities in the periods preceding and following ventilation indicate that the introduction of additional oxygen into the structure did not have an appreciable increase in thermal conditions. This would be expected, since the oxygen concentration at the 2 foot level during the pallets and straw experiments remains close to ambient conditions for the duration of the experiments. Since oxygen at this level is not depleted, the introduction of additional oxygen via ventilation would not be expected to increase combustion. Since the combustion rate would not be expected to increase, neither would the rate at which heat flux or temperature would increase. Rather these values would be expected to continue on the same trend as the pre-ventilation period until the fuel started to be consumed completely. Once again, this can be particularly seen in the similar behavior between the no vent case, Experiment 6, and the remote vent case, Experiment 3, which had temperature and ventilation profiles that were quite similar.

The peak heat fluxes and temperatures for the pallets and straw experiments occurred in the period following ventilation for the two experiments in which ventilation was performed, and near the end of the test for the no ventilation case. These peaks are listed in Table 4.6. The peak heat fluxes of 7.8 kW/m^2 and 7.6 kW/m^2 for Experiments 3 and 6, respectively were nearly identical, within the 8% error of the heat flux gauge. Experiment 7 had a 12.5% lower peak of 6.7 kW/m^2. The

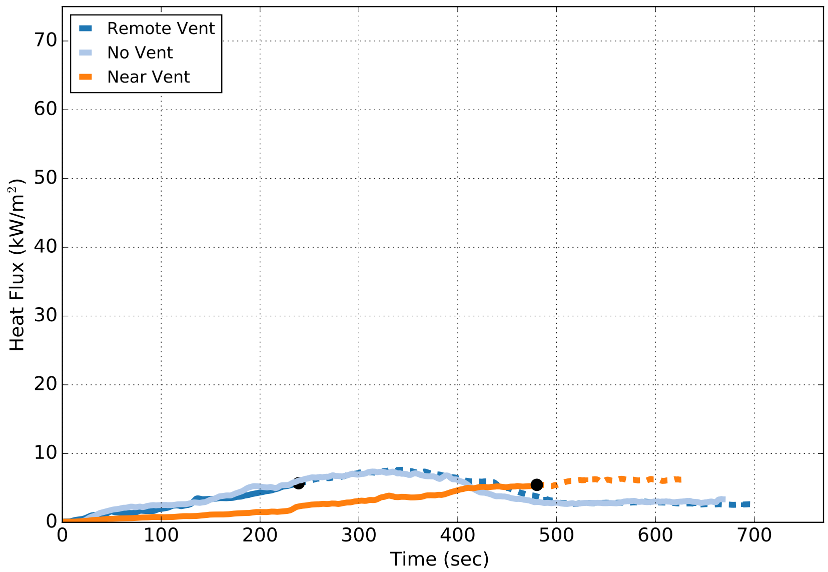


Figure 4.4: Room 201 Floor Heat Flux for Pallets and Straw Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

Table 4.6: Peak Thermal Conditions for Pallets and Straw Experiments

Experiment	**Peak Floor Heat Flux (kW/m^2)**	**Peak 3 Foot Temp. (°C)**	**Peak 7 Foot Temp. (°C)**
3 (Remote Vent)	7.8	165	557
6 (No Vent)	7.6	164	477
7 (Near Vent)	6.7	161	439

difference between this peak and the other two experiments is likely because Experiment 7 took longer to grow than the other two experiments, a fact which can be seen in Figures 4.4, 4.6, and 4.5. The peak 3 foot temperatures were all well within

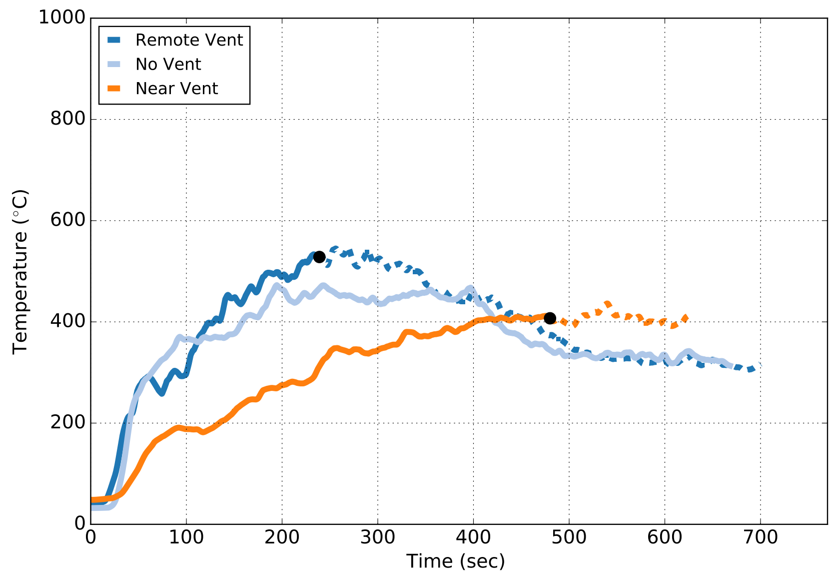


Figure 4.5: Room 201 7 ft. Temperatures for Pallets and Straw Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

the error of the thermocouple wire. The most variation between the peaks in the three tests was noted was noted at the 7 foot level, where the peak in Experiment 3 was 18% greater than that in Experiment 6, and the peak in Experiment 7 was 7.8% lower than that in Experiment 6. While the difference between Experiments 6 and 7 was within the error of the thermocouple, the peak in Experiment 3 was slightly above the uncertainty in the wire.

4.2.2 OSB Experiment Thermal Conditions

The oxygen concentrations in the OSB experiments demonstrated a similar trend to the pallets and straw experiments. Negligible depletion was noted at the

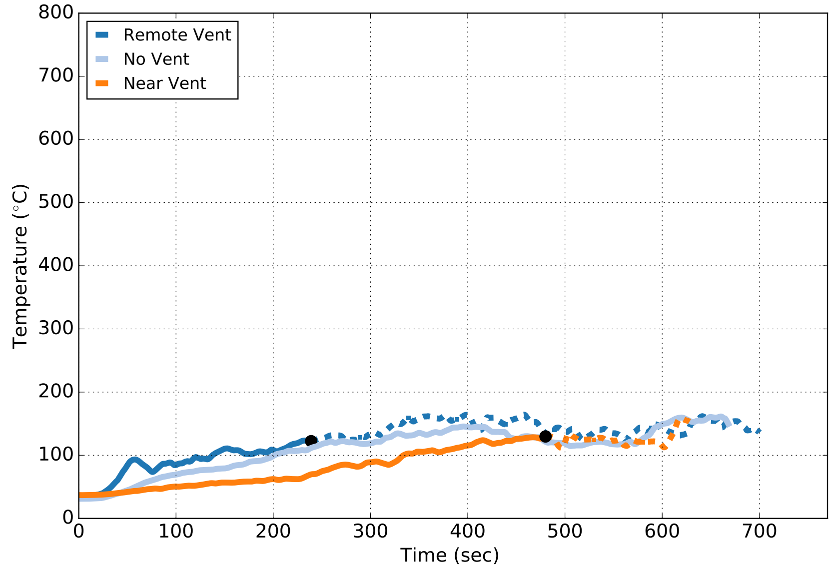


Figure 4.6: Room 201 3 ft. Temperatures for Pallets and Straw Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

2 foot sample points, but at the 6 foot level, oxygen concentrations decreased until the point of ventilation, at which point they recovered to levels closer to ambient, after a brief period of steady behavior. Although the oxygen concentration behavior between the two training fuels was similar, the thermal conditions noted in the OSB experiments were more severe. The 7 foot temperature profiles for Experiments 4 and 8 are shown in Figure 4.7. In Experiment 8, the 7 foot temperature increased 22% from 669 °C at the time of ventilation to a post-vent peak of 714. WHile this increase is significant, the slope of the 7 foot temperature curve did not increase in a significant way. °C. A more significant was noted in Experiment 4, the remote ventilation case, where the temperature at the time of ventilation was 669 °C. The

temperature decreased following ventilation, before rebounding to a post-vent peak of 683 °C). While the temperature changes from the pre- to post-ventilation period were not particularly notable at the 7 foot level, the floor heat flux and 3 foot temperature exhibited a more substantial change following ventilation, which can be seen in Figures 4.8 and 4.9.

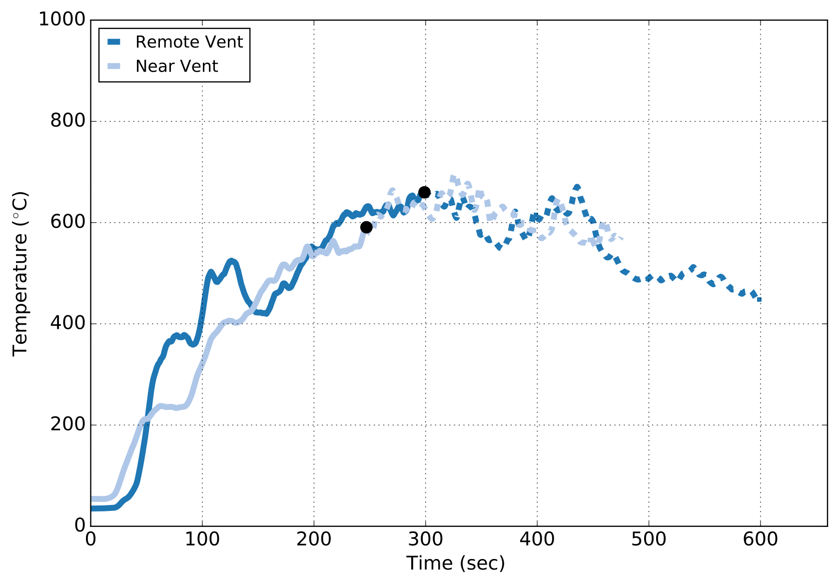


Figure 4.7: Room 201 7 ft. Temperatures for OSB Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

The post-ventilation behavior observed in the remote ventilation case (Exp. 4) was similar to the trends noted in the pallets and straw. That is, the rate at which temperature and heat flux increased did not change in a significant way. Rather, both values steadily increased until reaching a peak near the end of the test. While the trend was similar to the pallets and straw, the magnitude of the thermal

Table 4.7: Room 201 Thermal Peaks in Pre- and Post-Ventilation periods for OSB experiments

Experiment	Peak Heat Flux (kW/m^2)		Peak 3 Foot Temperature (°C)	
	Pre-Vent	Post-Vent	Pre-Vent	Post-Vent
4 (Remote Vent)	11.1	13.4	158	267
8 (Near Vent)	10.8	19.3	173	305

conditions was higher. The heat flux at the time of ventilation was 11.1 kW/m^2, which increased steadily to a peak value of 13.4 kW/m^2 following ventilation, as listed in Table 4.7. The temperature increased ina similar fashion from 158°C at the time of ventilation to a peak 267°C following ventilation.

The increases following ventilation in Experiment 8, the near ventilation case, were more pronounced. Immediately following ventilation, the slope of both the 3 foot temperature and floor heat flux curves increase markedly. Further, the increase in heat flux following ventilation is greater than was noted in the remote ventilation case, Increasing from 10.8 kW/m^2 at the time of ventilation to a peak of 19.3 kW/m^2. The peak value following ventilation was not significantly greater than that noted in Experiment 4, but this peak was reached sooner after ventilation, because of the increase in slop of the temperature curve. Thus, while the increased oxygen afforded by ventilation in Experiment 4 did not impact fire growth, the additional ventilation provided by opening the fire room window resulted in a marked increase in rate at which floor heat flux and 3 foot temperatures were increasing, as well as a more

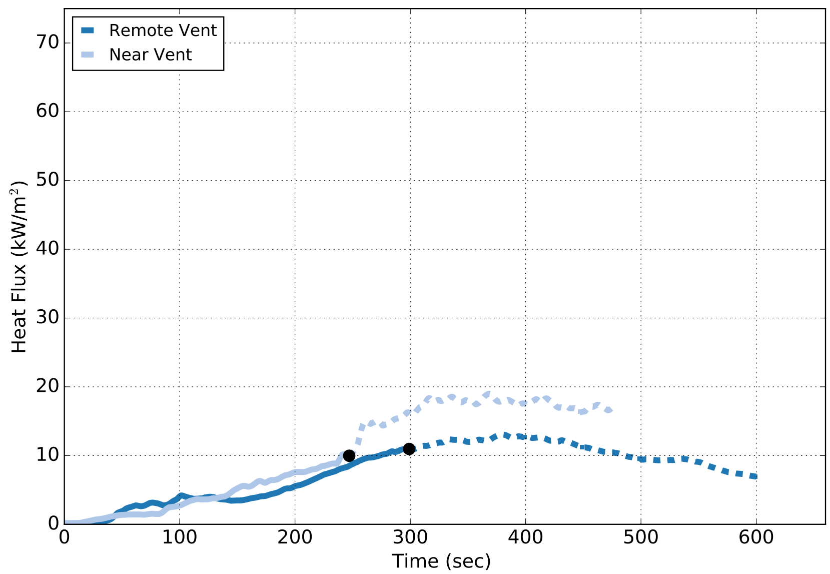


Figure 4.8: Room 201 Floor Heat Flux for OSB Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

severe peak heat flux in the fire room.

4.2.3 Furnished Room Experiment Thermal Conditions

The oxygen concentrations profiles from the three furnished room experiments showed the greatest amount of depletion, particularly at the 2 foot level. Oxygen concentrations consistent as low as 11% were noted prior to ventilation, and concentrations as low as 5% were seen in the rear of the fire room. This is consistent with underventilated codnitions, and is in stark contrast to the two distinct zones noted in the training fuel experiments. These reduced oxygen concentrations were a function of fuel load and composition, and contributed to the more severe thermal conditions detailed in this section.

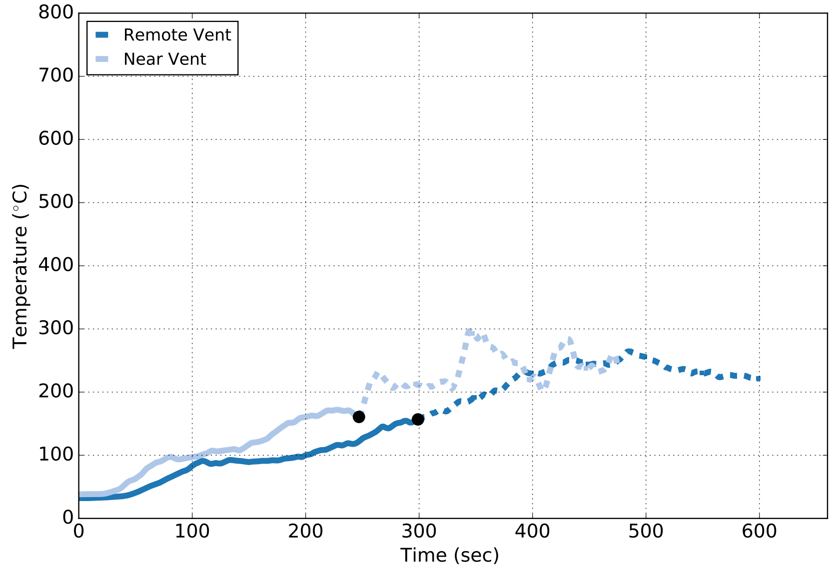


Figure 4.9: Room 201 3 ft. Temperatures for OSB Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

Figure 4.10 shows the 7 foot temperatures in the fire room for each of the furnished room experiments. Inspection of the temperature histories illustrates two differences between the furnished room 7 foot temperatures adn the traning fuels. First, the rate of temperature rise close to the ceiling does not drastically increase until later in the experiment than was noted for the training fuels. This is consistent with the results of the heat release rate data discussed in Section 3.3.2. Second, the temperatures at the 7 foot level are higher than those noted in the pallets and straw or OSB experiments. Table 4.8 shows that the ventilation experiments, the temperatures were 400°C and 409°C at the time of ventilation, increasing to 955°C and 726°C, respectively, for Experiments 1 and 5. In the no ventilation experiment, the peak 7 foot temperature was 727°C, and remained above 600°C from the 400 second mark until the end of the test.

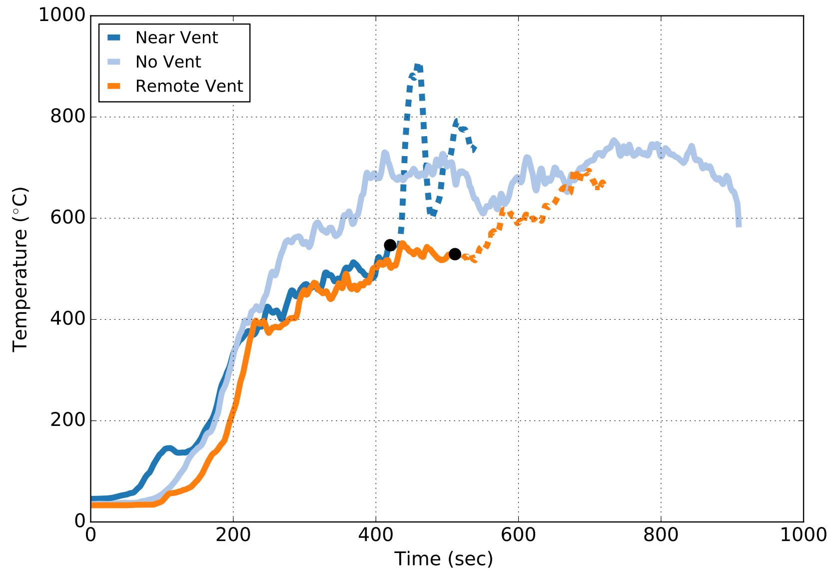


Figure 4.10: Room 201 7 ft. Temperatures for Furnished Room Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

In addition to more severe temperatures at the 7 foot level, the heat flux measured in the fire room during the furnished room experiments was considerably higher than the fluxes noted in the training fuel tests. Figure 4.11 shows these heat flux values. Just as was the case with the 7 foot temperatures, a significant rise in heat flux to the floor was not noted until later in the test than the training fuels. At the time of ventilation, The ehat flux was 18.4 kW/m^2 in the near vent case and 11.1 kW/m^2. Following ventilation, the peak heat flux observed in these tests was 150.2 kW/m^2 and 69.3 kW/m^2, respectively. In the no ventilation case, The heat

Table 4.8: Room 201 Thermal Peaks in Pre- and Post-Ventilation periods for furniture experiments

Experiment	Peak Heat Flux (kW/m^2)		Peak 3 Foot Temperature (°C)		Peak 3 Foot Temperature (°C)	
	Pre-Vent	Post-Vent	Pre-Vent	Post-Vent	Pre-Vent	Post-Vent
1 (Near Vent)	18.4	150.2	408	955	554	924
2 (No Vent)	80.2	-	602	-	747	-
5 (Remote Vent)	11.1	69.1	400	726	561	713

flux climbed steadily to 10 kW/m^2, followed by a rapid jump to above 55 kW/m^2, reaching a peak value of 80.2 kW/m^2. A similar rapid jump was noted following ventilation in Experiments 1 and 5. In the near vent case, the increase occurred almost immediately after ventilation, whereas the increase in the remote vent case was delayed.

The 3 foot temperatures, shown in Figure 4.12, observed in the furnished rooms mirrored the severe floor heat flux. Table 4.8 shows that temperatures in excess of 400°C were noted prior to ventilation for both the remote vent and near vent cases. After ventilation, temperatures consistent with postflashover conditions were noted. In the no vent case, the peak temperature close to the floor was 80.24 kW/m^2. The furnished room experiments exhibited considerably more severe thermal conditions than the pallets and straw or the OSB tests. In addition, the growth in conditions following ventilation is not only greater, but it occurs more rapidly than in the training fuel experiments. These differences in thermal conditions and response and

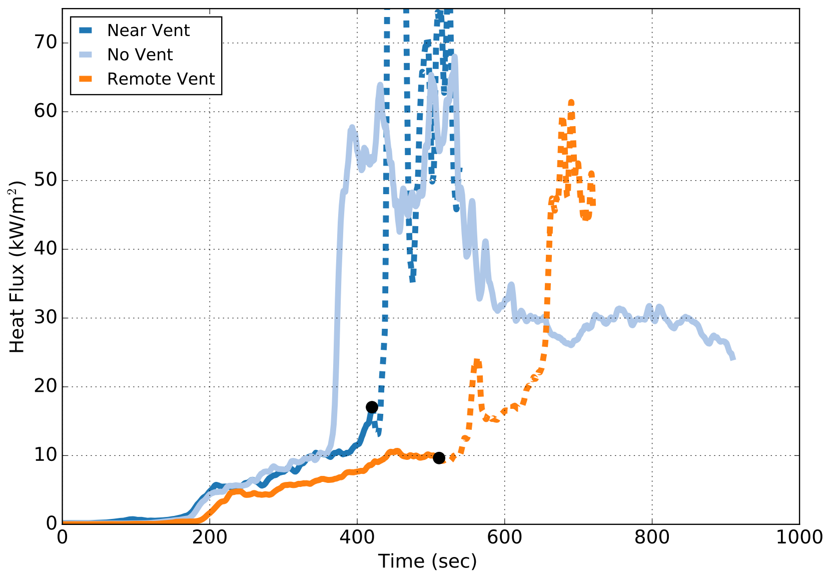


Figure 4.11: Room 201 Floor Heat Flux for Furnished Room Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

their effect on firefighting students will be explored in the following section.

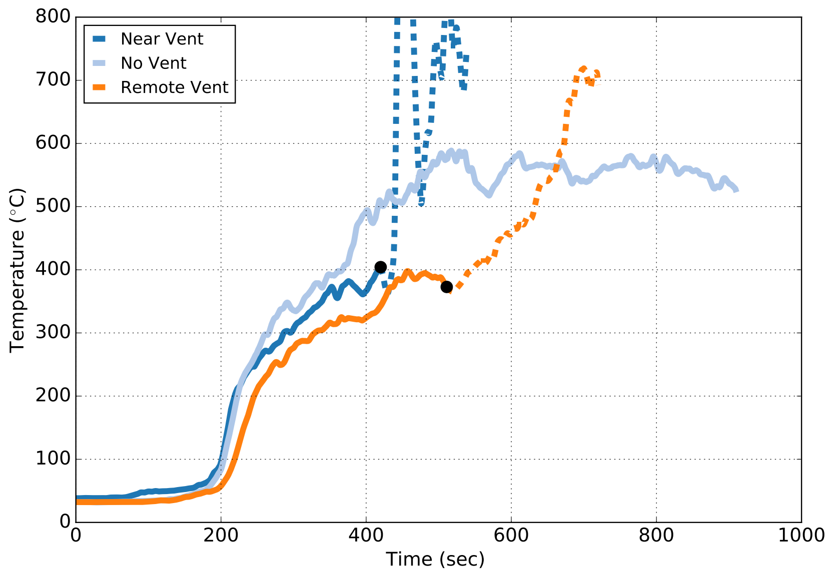


Figure 4.12: Room 201 3 ft. Temperatures for Furnished Room Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

Chapter 5: Discussion

This section will use the data presented in the Results section to compare the fuel loads used for the eight fire experiments. This discussion will be divided into two parts: one which will consider the fidelity of the training fuels and how they compare to a "real fire," and one which will address the safety of the conditions present in the fires.

5.1 Fidelity

Fidelity can be evaluated in a number of ways. Hartin [35] defines fidelity as, "the extent to which a simulation reflects reality." In essence, a live-fire training evolution is a simulation. The intent of any simulation varies with the objectives of the particular scenario, but the overall goal is to prepare firefighters for the fires that they will face in the field. If the simulation is considerably different than the model, which in this case would be a "real" residential fire, than the simulation may not be successful in preparing firefighters for challenges that they may face on the fireground. In the words of Hartin, "Improperly designed training may provide the learner with an inaccurate perspective of the fire environment which can lead to disastrous consequences." In other words, training which inaccurately portrays the fire environment, and how the fire environment changes as a result of firefighters' actions, can allow for the internalization of mistaken concepts, such as "ventilation always results in the improvement of conditions."

Hartin suggests that fidelity can be described in two ways, namely, functional and physical fidelity. Functional fidelity is the extent to which the simulation works and reacts realistically. In the context of fire dynamics, a training fire with high functional fidelity would respond similarly to fire department actions such as ventilation or suppression when compared to a furnished room fire. Physical fidelity, on the other hand, would be the extent to which a simulation looks and feels real. A training fire would exhibit a high degree of physical fidelity would have thermal and smoke conditions similar to those encountered in a furnished room. Many instructors focus on physical fidelity: aiming to create a fire that is "bigger and hotter" [14]. By creating a training fire with similar thermal conditions to those experienced on the actual fireground, however, instructors may be creating a fire environment that compromises the safety of the students or of the instructors themselves. Rather than focusing on recreating the severe thermal conditions experienced in real structures, instructors instead should focus on creating training fires with a high degree of functional fidelity. By mimicking the response of a furnished room to firefighters' actions, instructors can properly prepare students for the modern fireground while still maintaining a degree of safety and control over the fire scenario. The following sections will consider the two training fuels in terms of their physical fidelity and function fidelity to the furnished room fire.

5.1.1 Training Fire Peak Growth Occurs Early in the Fire

Figure 3.8 from Section 3.3.1 showed the heat release rate curves of the three fuel packages. Recall that the period in which the rate of increase of the HRR was largest was immediately following ignition. This rapid development in heat release rate and temperature can be attributed to the pyramid shape of the pallets and straw setup, which is conducive to fire growth. The fire is ignited in the straw, which begins to burn readily because of the high surface-area-to-mass ratio. The fire propagates through the straw in the center of the pyramid quickly, producing a sufficient amount of heat to ignite the pallets. The pallets make up the majority of the mass of the fuel, roughly 80%, and are responsible for the bulk of the total energy that is released. The total energy released by the pallets can be estimated by using the Equation 5.1, where m_{fuel} is the mass of fuel and ΔH_c is the heat of combustion. Heats of combustion of 19.2 MJ/kg for white pine and 15.6 MJ/kg for straw were used [36]. This leads to a theoretical total energy release for each of the three fuel packages. For the pallets and straw fuel package, the value computed was 1.26 GJ, 83% of which is attributed to combustion of the pallets. Although the pallets constitute the majority of the total energy released in the fuel package, the straw has a greater contribution to the heat release rate. Recall that the peak rate of increase in heat release rate, which was approximately 30 kW/s, occurred immediately after ignition in the pallets fuel package. This is also the period before the pallets have been ignited. Since the fire rapidly consumes the straw, the 18% of the total energy released by the straw is all released in this initial period, whereas the energy content of the pallets is released over the rest of the duration of the test.

$$Q = \Delta H_c m_{fuel} \tag{5.1}$$

Note that the theoretical total energy released, 1.26 GJ, is greater than the computed total energy released, which was 0.95 GJ. This represents a roughly 24% difference. if this difference was a result of unburned fuel, it would correspond to approximately 16.1 kg of unburned pallets. It is possible that this discrepancy is a result of unburned fuel, the uncertainty of the calorimeter, or both.

The OSB exhibited both a higher peak heat release rate and higher 7 ft. temperatures than the pallets and straw experiments. Immediately after ignition, the two fires develop similarly, which is consistent with expectations, since the OSB fuel package is ignited in a similar manner to the pallets and straw. The addition of OSB to the pallets and straw fuel package is responsible not only for the increase in total energy released, but is also responsible for the maintenance of a high HRR for a longer period of time than the pallets, resulting in a greater total energy release. The greater total energy release is unsurprising, since the two OSB sheets that were added each weigh as much as another pallet. A theoretical total energy released can be estimated using the fuel weights from Experiment 8 and the same method described above for the pallets. Assuming the sheets of OPB have the same heat of combustion as pine, which is reasonable since the primary composition of OSB is wood, the total mass of wood is 99.5 kg. The mass of straw is 13.9 kg. This yields a theoretical total energy release of 2.13 GJ. The addition of the

OSB sheets results in an approximately 90% increase in the potential energy, so the increase in measured total energy release describe in Section 3.3.1 is consistent with expectations. However, comparison of the OSB and pallets curves in Figure 3.8 shows that the OSB fuel package sustains an elevated HRR for linger than the pallets, a trend which can also be attributed to the vertically oriented OSB sheets. These sheets are exposed to the high heat fluxes in the plume of the fuel package, and the high surface area available for heating and the vertical orientation, which is conducive to flame spread, enable the maintenance of a higher heat release rate for a longer period of time than the pallets ands straw alone.

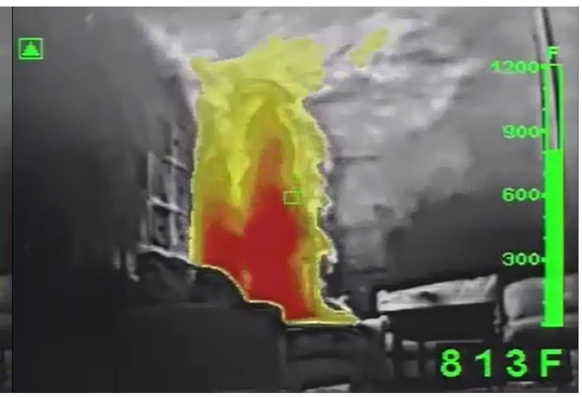
The temperature profiles and heat release rate histories observed in the furnished room fires indicate that the fire does not exhibit a period of rapid growth immediately after ignition. Rather, flame spread from the point of origin, which in this case was the corner of the couch, is rather slow. This is because the flame spread is not aided by geometry, as it is in the training fuel packages. in contrast to the training fuels, most of the fuel in the furnished room is located in the lower half of the room, meaning that flame spread most occur laterally to involve additional fuels. Whereas the contribution to the heat release rate from the OSB sheets in the plume is largely due to convective heat transfer, the fuels in the furnished room are heated primarily by means of radiation, both from the thermal layer and the seat of the fire. Consider Figure 5.1, which shows the IR camera view of the fire growth for the first 4 minutes of Experiment 5. The fire remains confined to the couch of origin for the first 4 minutes after ignition, when the arm of the second couch begins to burn. By this time, the fire is already quite large, but the heat transfer to other fuels within the room is not efficient, since this heat transfer is radiative in nature. Radiative heat flux decreases rapidly as distance from the source increases. So, even fuels that are close to the couch of origin, such as the second couch and the coffee table, are not ignited until a majority of the first couch is involved. By this time, the thermal layer has descended can be visualized by observing the couch along the back wall of the fire room. The color of the couch becomes progressively brighter as the surface temperature of the fabric increases due to heating. For the first 3 minutes of the experiment, the cushion of the couch that is closer to the seat of the fire is noticeably brighter than the further cushion. As the thermal layer descends, heating the second couch from above, the heating of the couch is more homogeneous, as indicated by the even coloring in the final three frames. This illustrates the contribution that thermal radiation from the hot gas layer has on fuels remote from the ignition point.

The heat release rate profiles in Section 3.3.1 showed that the heat release rate of the furnished room increased nearly 5 times as rapidly as the training fuels. The reason for this increased rate of growth is likely the fuel composition. The furniture was composed mostly of synthetic materials, such as polyurethane and polystyrene. These materials have different combustion characteristics than wood-based material [36]. A simple estimate of the potential energy can be performed by considering the contents of the furnished room as one of two materials: wood or polyurethane. Polyurethane has a heat of combustion of 23.90 MJ/kg [36]. If the couch and chairs are considered to be comprised of only polyurethane and the tables are considered to be comprised completely of pine wood, the total potential

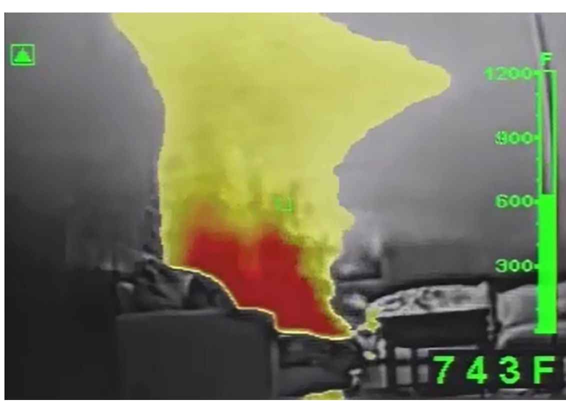
(a) 1:00

(b) 2:00

(c) 3:00



(d) 3:30



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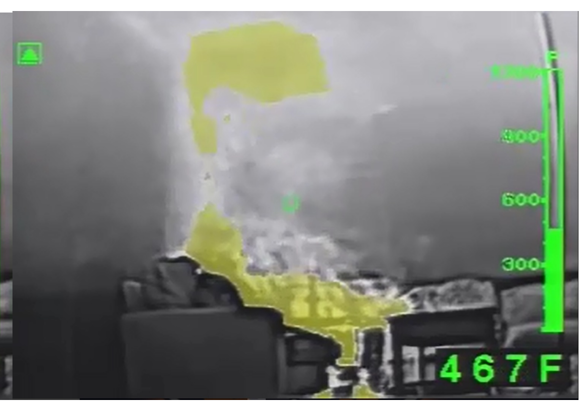


(f) 4:30

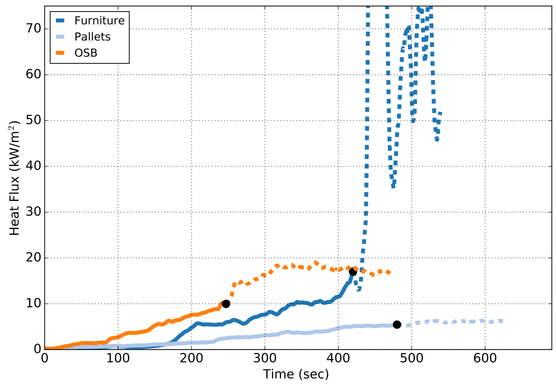
Figure 5.1: Fire Spread From Couch of Origin for Experiment 5

energy release would be 3.96 GJ. This fuel load is significantly larger than either of the other two fuel loads, and this larger amount of fuel helps contribute to the growth.

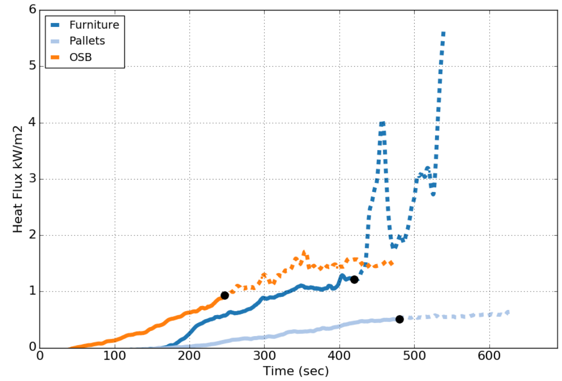
One of the most important differences between training fuels and fuels representative of those found in modern homes are that in the training fuels, the rapid initial growth is facilitated by the geometry of the fuel package. The pallets and OSB are arranged in such a way that once a sufficient quantity of straw is involved in the fire, these fuels begin to pyrolyze and burn. The result is a rapid, but not asymptotic, climb to the peak heat release rate. In the furniture fires, on the other hand, the growth to the peak heat release rate occurs when the hot gas layer has banked down sufficiently to heat fuels remote from the point of origin to the point where they pyrolyze. As these fuels begin to pyrolyze and burn, they contribute to the gas layer, increasing the heat release rate, and thus the temperature of the layer. This transition to the peak pre-ventilation thermal conditions of the fire is approximately 5 times faster than was noted in either of the training fuel experiments. The rate of this growth is significant because it occurs more quickly than firefighters would be able to recognize and react to it. If students do not recognize the difference in growth between furnished fires and training fires, they may be unprepared for it on the fire ground.

In the context of the training fire evolution, the timing of the growth of the fire is important. In a typical training evolution, the fire would be ignited by an instructor or a stoker and allowed to develop for a period of time before allowing the trainees to begin the evolution. Even after the determination is made that the evolution can begin, there is likely to be an additional delay before the firefighters actually approach the fire compartment because of the time associated with various fireground tasks such as hoseline advancement. Consider the heat release rate and fire room temperature and heat flux charts for the fire room ventilation experiments in Figure 5.2. In the pallets and straw, there is no significant increase in either temperature or heat flux at any point in the test. In the OSB, there is a more significant increase, but this increase is noted early in the experiment, possibly before the firefighters make entry. This would mean that the trainees would not experience a rapid change in thermal conditions. Rather, the changes in heat flux and temperature would be more gradual. Inspection of the furnished room heat flux and temperature profiles reveals that there is a rather quick change in temperature and heat flux, and this increase is experienced later in the experimental time line. In a furnished room, the transition to these more severe thermal conditions would be well within the firefighters timeframe, and would have the potential to harm them.

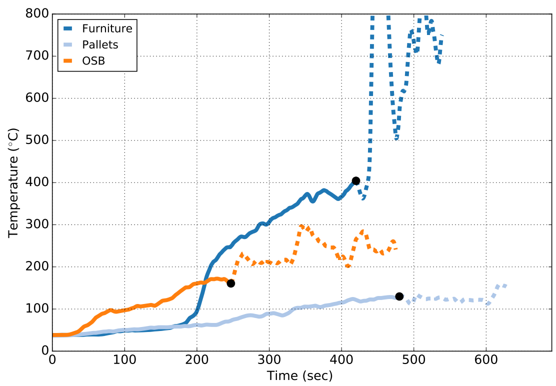
Consider Figure 5.3, which shows the growth of the pallets and straw fire as the instructors would see it compared to the development of the temperatures. The temperature charts reveal that the most rapid growth, particularly at higher elevations within the room, occurs within the first 60 seconds. At this time, the fire is not very visually impressive: the majority of the fuel burning at this time is still the straw, and the pallets are not yet well involved. An instructor may not think that the training fire is developed enough to begin the evolution. At 90 seconds or 120 seconds from ignition, the pallets have become more involved, but at this point, the growth rate of the ceiling temperatures has dramatically decrease, approaching



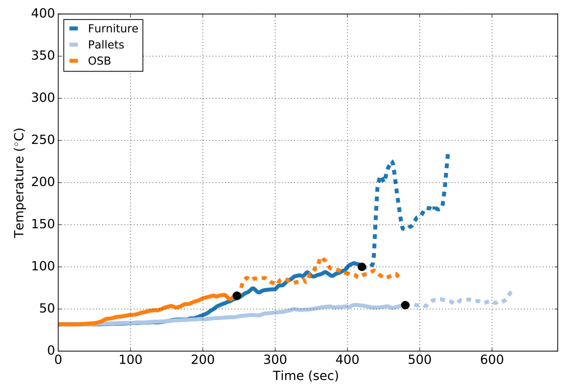
(a) Room 201 Heat Flux



(b) Room 202 Heat Flux



(c) Room 201 3 ft. Temperatures

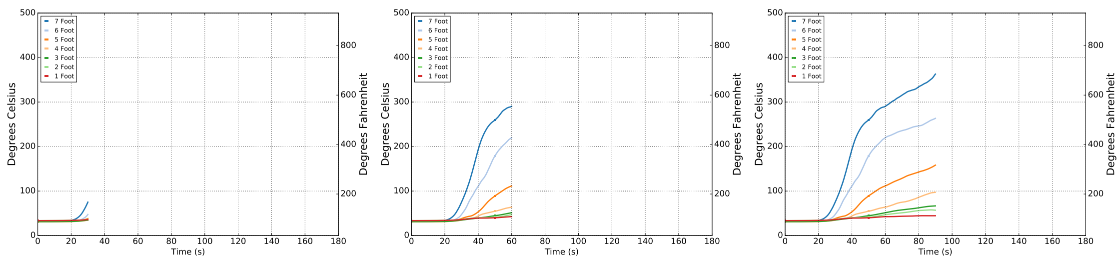


(d) Room 202 3 ft. Temperatures

Figure 5.2: Heat Flux and 3 ft. Temperatures for Fire Room Ventilation Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

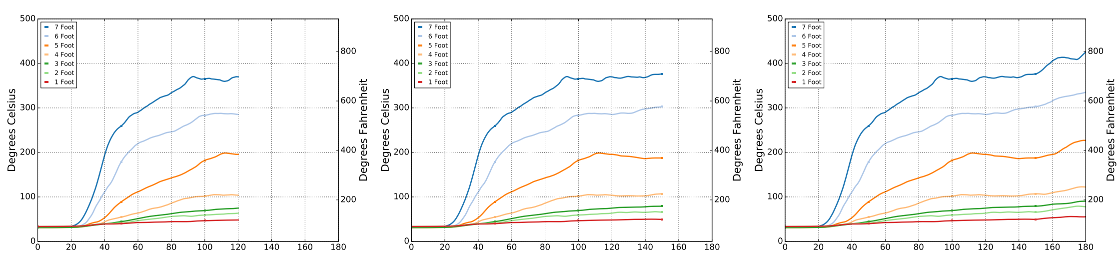
a steady state. Consider that the instructor elected to start the evolution at 90 seconds, when visually, the pallets are beginning to become involved. Assuming that the students take 30 seconds to advance into the fire compartment, the growth of the fire has already reached a steady state, and the students will not be exposed to any sort of significant temperature rise during their evolution. Thus, visual observation of a training fuel package is a counterintuitive indicator of the appropriate time to begin a training evolution, if the goal is to expose students to a growing fire, as they would likely encounter on the fireground [5, 6].

(a) 30 Seconds **(b)** 60 Seconds **(c)** 90 Seconds



(d) 30 Seconds **(e)** 60 Seconds **(f)** 90 Seconds

(g) 120 Seconds **(h)** 150 Seconds **(i)** 180 Seconds



(j) 120 Seconds **(k)** 150 Seconds **(l)** 180 Seconds

Figure 5.3: Visual Growth of Pallets vs. Temperature Development

5.1.2 Training Fuels Do Not Create Thermal Conditions Consistent With Flashover

In recent years, several firefighter line of duty death or injury incidents have occurred where failure to identify worsening thermal conditions has been identified as a contributing factor. Thus, if firefighter trainees are entering a training structure after the initial growth of the training fire, they may be missing an important concept: that worsening thermal conditions are a dangerous situation that may require a re-evaluation of strategy. The possible lack of a rapidly growing fire due to training evolution timelines highlights another important discrepancy between training fuels and fuels that are representative of those found on the fireground: since training fuels are restricted to wood products, in order to be compliant with NFPA 1403, they lack the heat content of the synthetic materials commonly found on the modern fireground. The adage "You are not fighting your grandfather's fire anymore" [6] emphasizes the fact that the fuels that firefighters use to train have less potential for hazard than those they would encounter on the fireground. For example, compare the maximum thermal conditions noted in each of the fuels.

The thermal conditions observed in each of the three furnished room experiments were consistent with post-flashover conditions, which are commonly defined as 20 kW/m^2 to the floor or 600°C [37] at the ceiling. Other sources define the onset of flashover as 590°C in the upper layer. This "upper layer temperature" comes from a simple, two-zone compartment fire model. This model assumes that there are two thermal zones, a hot upper layer and a cooler, lower layer. Each zone is a single, homogeneous temperature, and the two zones are separated by an interface, whose height is labeled z_{int}. While it is important to recognize that the two zone model is merely an approximation, and that the actual temperature profile within a room is continuous profile, knowledge of the height of the interface and the approximated gas layer temperature, T_u, can give a simple, useful insight into the temperature profile within the room. Several methods exist for predicting the interface height of the hot gas layer, and the resulting temperature of said layer. One method used is outlined in the FDS Validation guide [38]. In this method, the floor-to-ceiling temperature profile is considered to be a continuous function, $T(z)$. Integration of $T(z)$ from the floor (z = 0) to the height of the room, H, yields a quantity, I_1. Using the assumption that the upper and lower gas layers are each a uniform temperature throughout, it can then be said that the I_1 is then equal to the sum of two terms: the product of the upper gas layer temperature and the distance between the interface height and the height of the room and the lower gas layer temperature and the interface height. I_1 is defined in Equation 5.2.

$$I_1 = \int_0^H T(z)dz = (H - z_{int})T_u + z_{int}T_l \tag{5.2}$$

A similar method can be used to calculate a second term, I_2. In this instance, rather than integrating the temperature profile, the integral of the inverse of the temperature profile is taken. Using the same assumption as stated above, I_2 is defined as shown in Equation 5.3. By solving for z_{int}, the interface height, and combining the two equations, an expression for the interface height is then obtained, as shown in Equation 5.4. In this equation, I_1 and I_2 are defined above, H is the height of the room, and T_l is the temperature of the lower gas layer. It assumed that T_l is equal to the temperature recorded in the lowest grid cell [FDS].

$$I_2 = \int_0^H \frac{1}{T(z)} dz = (H - z_{int})\frac{1}{T_u} + z_{int}\frac{1}{T_l} \tag{5.3}$$

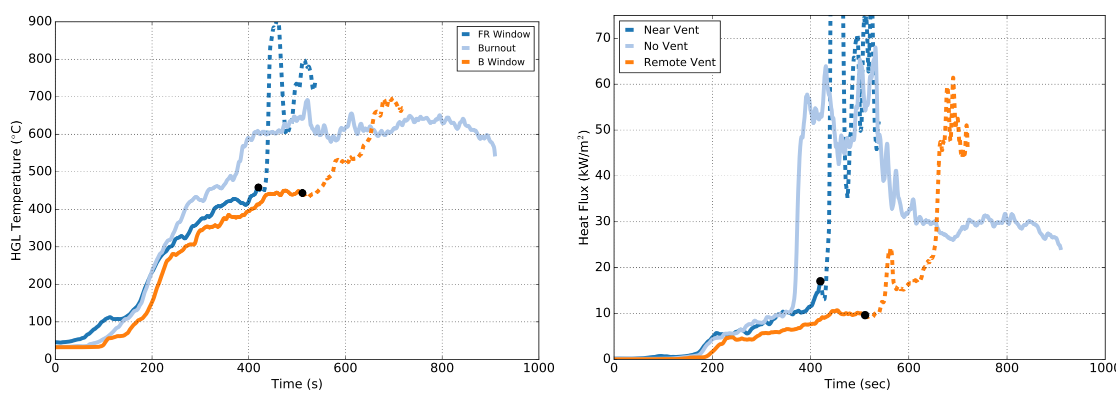
$$z_{int} = \frac{T_l(I_1 I_2 - H^2)}{I_1 + I_2 T_l^2 - 2T_l H} \tag{5.4}$$

The layer interface height as a function of time for each of the experiments is presented in Appendix A.Once the interface height has been calculated, the hot gas layer temperature can then be computed by integrating the temperature profile, $T(z)$, from the interface height, z_{int}, to the ceiling height, H, and dividing by the total height of the upper gas layer, $H - z_{int}$, as shown in Equation 5.5.

$$T_u = \frac{\int_{z_{int}}^H T(z)dz}{H - z_{int}} \tag{5.5}$$

For these experiments, integration for the I_1 and I_2 terms, and for T_u, was performed numerically using a right hand scheme. The thermocouple trees had thermocouples every 1 foot from 1 foot off the ground to 7 feet from the ground (1 foot from the ceiling). Each thermocouple was assumed to define the temperature for 6 inches in either vertical direction from the thermocouple. Additionally, the 1 foot and 7 foot thermocouples were assumed to cover the 1 foot space between the sensor and the floor or ceiling. The resulting hot gas layer temperature profiles can be used to explain the flashover phenomenon of the three fuels.

Figure 5.4, which shows the floor heat flux in the fire room for the furnished room experiments, shows that the heat flux criteria for flashover is exceeded for each of these tests. In Experiment 2, the maximum temperature recorded at the 3 ft. level was 598.9 °C and the heat flux to the floor in Room 201 was 80.2 kW/m^2. These conditions are typical of those that would be observed in a post-flashover compartment fire. In Experiments 5 and 1, conditions consistent with the onset of flashover were noted noted prior to ventilation, but after ventilation, the 3 ft. temperature and floor heat flux were 69.3 kW/m^2 and 726.0°C and 69.7 kW/m^2 and 954.6°C for Experiments 5 and 1, respectively. These are also consistent with a post-flashover fire.

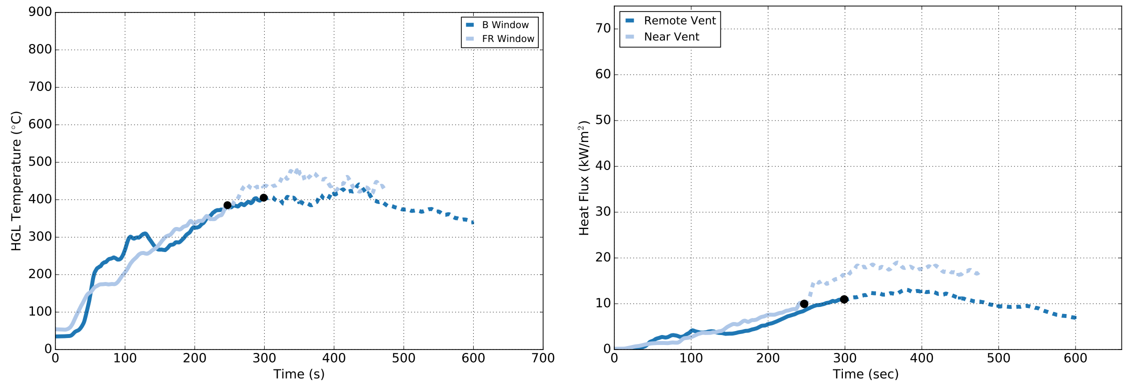


(a) Room 201 Hot Gas Layer Temperature

(b) Room 201 Floor Heat Flux

Figure 5.4: Floor Heat Flux and Hot Gas Layer Temperature in Room 201 for Furnished Room Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

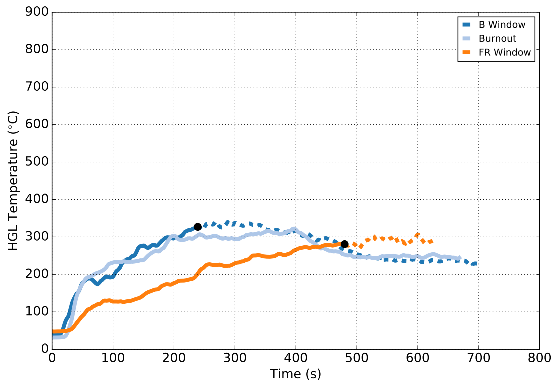
Peak thermal conditions in the fire room for the training fuels were never consistent with the onset of flashover or with post-flashover conditions. The training fuel scenario that came the closest to replicating these conditions was the fire room ventilation scenario for the OSB fire, which exhibited a peak heat flux of 19.3 kW/m^2 and a peak 7 ft. temperature of 714°C, observed after fire room ventilation. While these conditions are severe, they did not precipitate transition to flashover. There are several possible reasons that the fire in this case was unable to transition to flashover. Since the gas layer temperature was lower than 600°C, which can be seen in Figure 5.5, which is used as an approximation of the autoignition temperature of carbon monoxide, the gases in the upper layer were not at a high enough temperature to burn. If the gas layer temperature was higher, then these gases may have been able to burn remotely from the seat of the fire, as was seen in the furnished room fires. The additional heat release afforded by the burning gases may have resulted in conditions consistent with flashover. Similarly, although the heat flux to the floor was quite high in the fire room, there was no fuel along the floor that was exposed to this flux. In the furnished rooms, most of the fuel was located close to the floor, meaning that it was exposed to radiation from the gas layer, which heated these fuels to their pyrolysis points. In the OSB fire, all of the fuel is concentrated in the fuel package. so, while radiation from the layer contributes to the heating of the fuel package, this heating does not have the same contribution to fire growth as in the furnished rooms. Thus, it can be said that in addition to the greater amount of fuel that is present in the furnished room, this fuel is in a more efficient arrangement for radiant heat from the thermal layer to precipitate additional pyrolysis and growth of the thermal layer, transitioning the room to flashover.



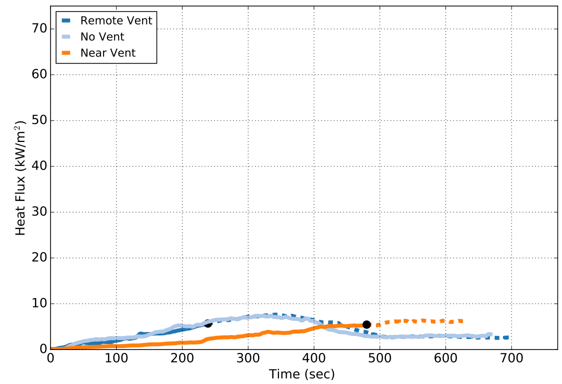
(a) Room 201 Hot Gas Layer Temperature **(b)** Room 201 Floor Heat Flux

Figure 5.5: Floor Heat Flux and Hot Gas Layer Temperature in Room 201 for OSB Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

The other training fuel experiments exhibited considerably lower heat fluxes and maximum gas layer temperatures. In Experiment 4, the maximum temperature recorded was 683°C and the maximum heat flux was 13.4 kW/m^2. In the pallets and straw fires, the 7 ft. temperature never exceeded 560°C and the peak fire room heat fluxes never exceeded 8 kW/m^2. It is possible that with additional fuel, the OSB experiments would have been able to achieve conditions consistent with flashover.



(a) Room 201 Hot Gas Layer Temperature



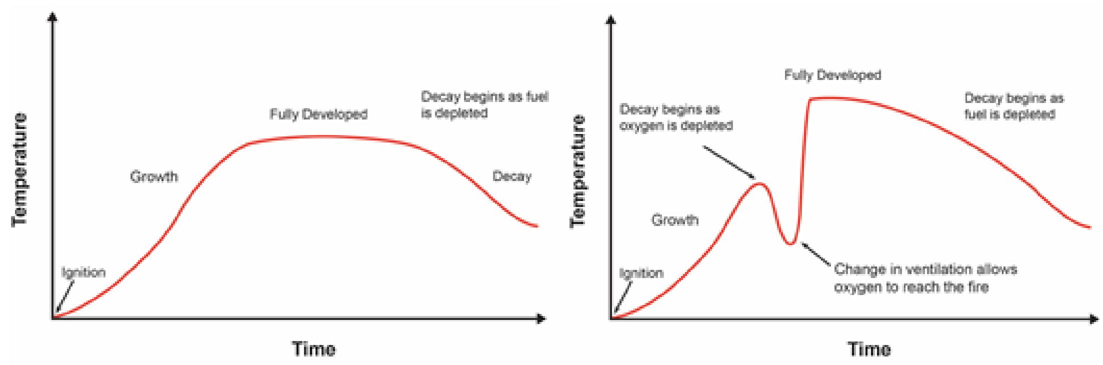
(b) Room 201 Floor Heat Flux

Figure 5.6: Floor Heat Flux and Hot Gas Layer Temperature in Room 201 for Pallets Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

Among the requirements set forth in NFPA 1403 is, The fuel load shall be limited to avoid conditions that could cause an uncontrolled flashover or backdraft [7]. Given the flashover conditions that were noted in each of the furnished room experiments, it is obvious that a full room of furniture would not be permissible with NFPA 1403. The pallets and the OSB, however, did not exhibit conditions consistent with flashover. Although the criteria for flashover were not reached, thermal conditions in the fire room were still quite severe, with heat fluxes to the floor above 13 kW/m^2 at their peak. Thus, while NFPA 1403 restricts fuels from creating uncontrolled flashover conditions, the severe, potentially hazardous conditions present in the fire room in the OSB fires are still permissible. When considering the potential for flashover, the functional fidelity of the training fuels is low, since neither fuel load produced conditions consistent with flashover, as was noted in the furnished rooms. This should be viewed as a positive aspect, however, since flashover in training fires is undesirable for a number of reasons, including safety and NFPA 1403 compliance. Since the thermal conditions noted in the furnished room fires were more severe than those noted in the OSB and pallets experiments, the training fires it would be expected that the training fires would have a low physical fidelity.

5.1.3 Fires in Concrete Training Buildings Do Not Exhibit Ventilation-Limited Decay

Traditionally, firefighters were taught that the life cycle of a fire consisted of four stages, as shown in the left image in Figure 5.7. These four stages were ignition, growth, fully developed, and decay. These stages were somewhat independent of fire department intervention, and decay was said to either occur when the fuel was totally burned away or when water was applied to the fire. Among the tactical considerations identified in recent fire dynamics research [5,6] is that this traditional fire growth curve taught to firefighters is not indicative of the time-temperature profiles noted in residential fires with modern furnishings. Rather, the development of the fire is better described by the chart presented on the right side of Figure 5.7 [6]. The difference between the two charts reflects the increased demand for oxygen in the combustion of modern, synthetic fuels. Table 5.1 lists the stoichiometric oxygen to fuel mass ratios for three wood products (pine, oak, and Douglas fir) and four types of flexible polyurethane foam, representative of the foam that would be found in the couches or chairs in the furnished room. On average, the polyurethane products require just less than twice as much oxygen for complete combustion than the wood products. This means that, for equal masses of fuel and a constant rate of air entrainment, combustion of polyurethane results in less efficient combustion.



(a) Legacy **(b)** Modern

Figure 5.7: Legacy Fire Curve vs. Modern Fire Curve

Table 5.1: Required Oxygen for Stoichiometric Combustion vs. Available Oxygen in Structure

Material	**Formula**	Ψ_O
Wood (pine)	$CH_{1.7}O_{0.83}$	1.21
Wood (oak)	$CH_{1.7}O_{0.72}N_{0.001}$	1.35
Wood (Douglas fir)	$CH_{1.7}O_{0.74}N_{0.002}$	1.32
GM21 PU Foam	$CH_{1.8}O_{0.30}N_{.05}$	2.24
GM23 PU Foam	$CH_{1.8}O_{0.35}N_{.06}$	2.11
GM25 PU Foam	$CH_{1.8}O_{0.32}N_{.07}$	2.16
GM27 PU Foam	$CH_{1.8}O_{0.30}N_{.08}$	2.21

These ratios in Table 5.1 can be used to estimate the amount of air required for stoichiometric combustion of the fuel packages used in these experiments. The Ψ_O values for pine can be used to approximate the wood products, such as pallets, straw, and the wooden furniture, and polyurethane can be used to represent the synthetic materials, such as the couches and chairs. Note that this method assumes that the couch and chairs are homogeneously made of polyurethane, which is not the case, since the couches have a wood frame. Since the exact weights of each component of the furniture items is unknown, however, this assumption will suffice. Equation 5.6 shows how the product of the Ψ_O values in Table 5.1 and the weight of the fuel component give the total mass of oxygen that is required for stoichiometric combustion. Dividing this value by the density yields the volume of oxygen required, which can then be divided by the volume fraction of oxygen in ambient air to find the volume of air that is required for stoichiometric combustion of the fuel package. Table 5.2 lists these results for the three fuel packages, assuming all wood is pine and all polyurethane foam is GM 25, which was chosen because of its intermediate value of Ψ_O.

$$V_{O_2,stoich} = \frac{m_{fuel}\Psi_O}{\rho_{O_2}} \tag{5.6}$$

$$V_{air,stoich} = V_{O_2,stoich}/\Phi_{air} \tag{5.7}$$

Table 5.2: Required Oxygen for Stoichiometric Combustion vs. Available Oxygen in Structure

Material	Mass of Fuel (kg)	Vol. O_2 Required for Stoich. combustion (m^3)	Vol. Air Required for Stoich. Combustion (m^3)
Pallets	54.3	49	236
OSB	99.5	118	564
Funriture	92.5 (wood), 140.0 (polyurethane)	302	1446

The pallets and straw fire requires the least amount of oxygen for complete combustion to occur. The larger fuel mass in the OSB fuel package required a corresponding greater volume of oxygen for complete combustion. The furnished room required the most oxygen for complete combustion, roughly 3 times more than OSB and 6 times more than furniture. This large difference is a result of both the larger weight of fuel in the furnished room but also the increased amount of oxygen that is needed for these fuels to burn to completion.

Compare these figures to the volume of the concrete burn structure, which is approximately 537m^3.If the amount of oxygen present at the time of ignition inside of the structure is less than the amount that is required, the fire will become underventilated, and decay if no additional ventilation is provide, hence the differently shaped curves in Figure 5.7. From the results of Table 5.2, this would indicate that the OSB and furnished room fuel packages would not be able to burn to completion, assuming no additional ventilation was provided.

The temperature profiles in the training fires in the concrete burn building in these experiments were more representative of the legacy fire curve than the modern fire curve, even in the experiments featuring furniture as fuel. This trend is most evident in the no ventilation experiments, where no doors or windows were opened during hte duration of the test. The 7 ft. temperature profiles for the no ventilation experiments are shown in Figure 5.8. These experiments did not display the ventilation-limited decay identified in compartment fires [5, 6]. Rather, temperatures continuously increased until reaching a plateau. This would indicate that the burn building is not well sealed, and indeed there is a significant amount of leakage through the built in openings of the structure, such as the scuppers.

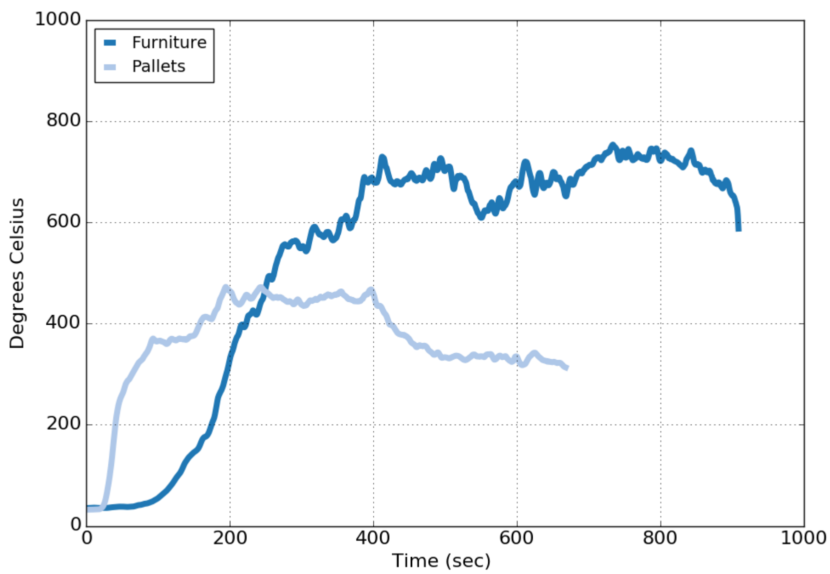


Figure 5.8: 7 ft. Temperatures for No Vent Experiments

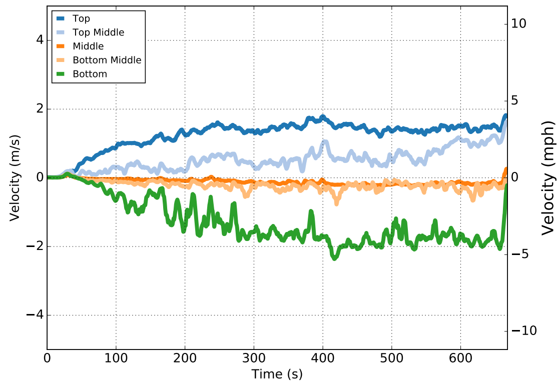
While these built-in openings are small when compared to a window or door, the total area of these openings sums becomes significant, as shown in Table 5.3.

The total leakage area across the three floors of the building is 821.5 in^2, which would be equivalent to a small window. These openings allow the free flow of air into the structure, meaning that instead of a fixed amount of oxygen present in the building, as would be the case in a well-sealed residential structure [39], there is a constant source of fresh air for the fire to draw upon. in the concrete burn building experiments, this constant flow of air was confirmed by the bidirectional probes in the fire room doorway.

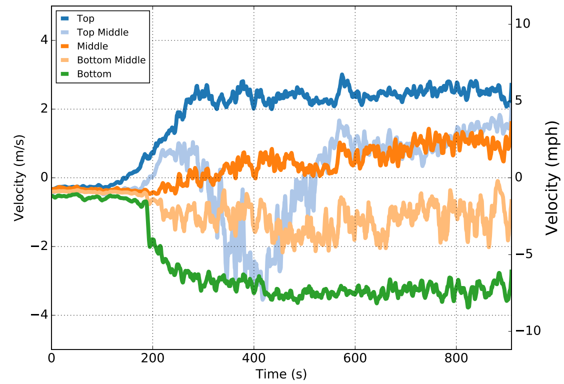
Table 5.3: Leakage Areas for Concrete Structure

Floor	Leakage Area (in^2)
1	145.5
2	404
3	272

The doorway gas velocities for the no vent experiments are shown in Figure 5.9 for the pallets and straw and the furnished room. The velocities for the no ventilation experiments are consistent with a bidirectional flow path, with oxygen entering the fire room low, indicated by the negative velocities, and products of combustion being exhausted out of the top of the doorway, indicated by the positive velocities. In a well-sealed residential home, if no exterior ventilation was provided, these velocities would be expected to decrease as the oxygen concentration decreased, a trend identified in [6]. This reduction in velocity was not seen, indicating that the



(a) Pallets and Straw



(b) Furniture

Figure 5.9: Fire Room Door Velocities. Probes are spaced equidistantly inside the door, at 13 inches, 26 inches, 39 inches, 52 inches, and 65 inches from the ground. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

fires in the concrete buildings did not enter a decay stage.

The constant supply of air through leakage points affects the oxygen concentrations and fire dynamics in the fire room. Recall Figure 4.3, which showed the oxygen concentrations for the furnished room experiments. Oxygen concentrations in the rear of the room, where the leakage air from the scuppers was not able to reach, declined to 5% and remained there for the duration of the experiment. On the other hand, the oxygen concentrations in the doorway were close to 15% during this period. This means that oxygen was being provided to the fire room at a high enough concentration to sustain burning in that area, which is the reason for the maintenance of high temperatures close to the ceiling seen in Figure 5.8. The oxygen concentrations close to the floor, displayed in Figures 4.1 and 4.2, remained close to ambient concentrations. This means that the fire was not producing a sufficient amount of combustion products to bank down to the floor level and reduce oxygen concentrations.

Built-in leakage points, such as the scuppers in the concrete burn building, are not a feature of the homes to which firefighters would be responding. In the average residential home, the minimum amount of leakage between the house and the environment is desirable, as it makes the home the most efficient in terms of energy [39]. For the same reason, the amount of air that is able to be entrained into one of these structures is quite small, and when compared to the amount of air that is able to be entrained into a compartment by a window or door it is negligible. Thus, in a building such as this, if no exterior ventilation openings are available for air exchange between the structure and the environment, the only oxygen that is available for the fire to burn is in the air that is in the structure prior to ignition.

It is important that firefighters recognize and understand this difference. If firefighters were to make entry into a well-sealed residential structure where the fire had already begun to decay, they would be greeted initially by less severe thermal conditions [6]. These conditions are likely to increase in severity as air is allowed to enter behind the firefighters as they advance in their fire attack. The quickness of the fire's response to ventilation depends largely on the thermal conditions at the time of ventilation and the amount of ventilation that is provided as firefighters enter the structure, and in some cases can be quite rapid. In contrast to the well-sealed structures of the modern residential environment, the fire in the concrete training building maintains a steady flow of oxygen through the lower part of the fire room. This means that it is not as starved for oxygen as the fire in the regular building, and, while the fire does increase in size following ventilation, it is not with the severity that has been documented in modern residential structures.

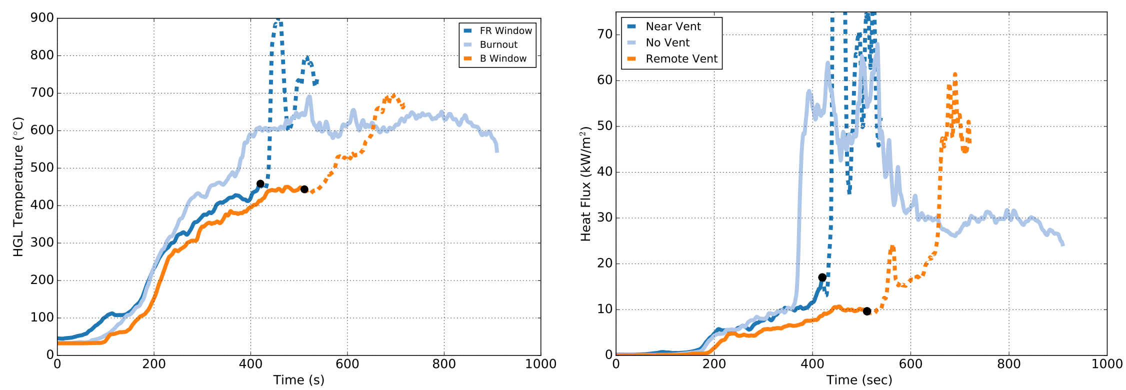
5.1.4 Training Fires Have Limited Response to Ventilation

Conventional firefighting tactics have dictated that "venting equals cooling" [40]. In short, this means that fire department initiated ventilation will result in the expulsion of products of combustion, and not cause an increase in the size of the fire. In recent years, there has been a paradigm shift away from this notion, where it is now widely emphasized that ventilation only results in the improvement of conditions when the venting occurs in coordination with water application by the suppression team.

Part of the reason for this misunderstanding can be attributed to the nature of natural fuels when compared to modern fuels. Kerber [6] conducted experiments comparing legacy furniture to modern furniture in an identical residential structure. Among the differences that were noted to the two fires were the peak temperature and minimum oxygen concentrations noted prior to ventilation, 600°C and 5% for the modern fuel and 230°C and 18% for the legacy fuel. The most important difference when considering the importance of well-timed ventilation, however, was the time that elapsed between ventilation and flashover, which was 2 minutes for the modern fuel and 8 minutes for the legacy fuel. Obviously, the modern fuel responds much more quickly to changes in ventilation, whereas the legacy fuel takes approximately 4 times as long to reach flashover. This is significant because in legacy fires, there is a significant amount of time for firefighters to get a hoseline in place to suppress the fire, even in the presence of uncoordinated ventilation. That timeline is far more constricted in modern fires, where uncoordinated ventilation can result in untenable conditions for firefighters in full PPE if a hoseline is not in place. Thus, the modern fire is far less forgiving when considering the timing of ventilation.

Two ventilation cases were examined in these experiments: a remote ventilation case, where the window in Room 204 and the front door on the ground floor of the structure were opened, and a fire room ventilation case, where the window in Room 201 was opened. In [6], Kerber additionally examined the effect of vent location on the response of the fire. These tests indicated that ventilation points remote from the fire room resulted in a delayed transition to flashover compared to when the vent point was within the fire room itself.

The trend observed in the furnished room experiments is consistent with the findings described in [6]. The hot gas layer temperature and heat flux are given in Figure 5.10. In Experiment 1, which was the test in which the fire room window was ventilated, it can be seen that the hot gas layer temperature increased dramatically almost immediately upon opening the window. Conditions consistent with flashover are noted soon after ventilation. In Experiment 5, the remote ventilation experiment, temperatures take longer to increase following ventilation, finally reaching flashover at close to 150 seconds after ventilation. Both rooms transitioned to flashover following ventilation, indicating that they were underventilated prior to ventilation, although the response of the remote vent case was delayed. Thus, the furnished room experiments, the post-ventilation fire growth was consistent with trends noted for similar ventilation configurations conducted in wood-framed residential structures.



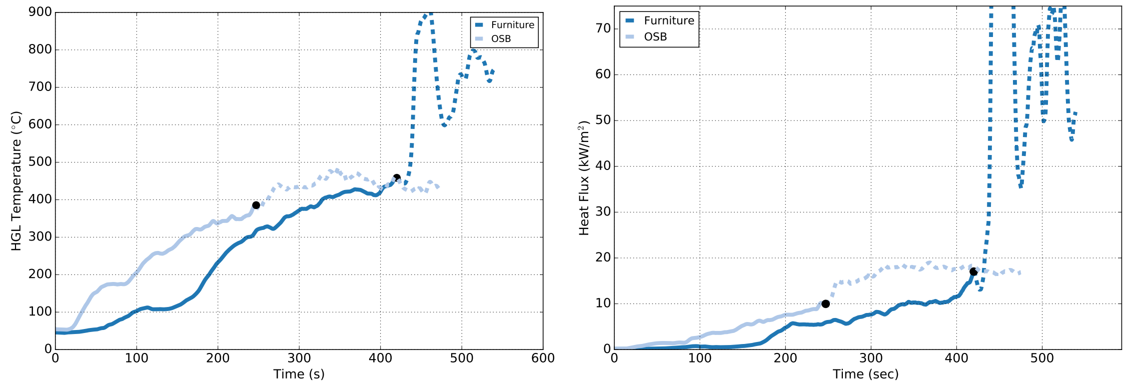
(a) Room 201 Hot Gas Layer Temperature

(b) Room 201 Floor Heat Flux

Figure 5.10: Hot Gas Layer Temperature and Heat Flux to Floor in Fire Room for Furnished Room Experiments. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

In the OSB experiments, the fidelity of the post-ventilation temperature trend varied between the two ventilation scenarios. In Experiment 8, which was the fire room ventilation case, the hot gas layer temperature increased by approximately 100 °C following ventilation. Additionally, there is a notable increase in the floor heat flux from 10 kW/m^2 to 15 kW/m^2 in Room 201 immediately following fire room ventilation. This increase is consistent with that noted in Experiment 1. After the initial increase, floor heat flux in the fire room increases to over 19 kW/m^2

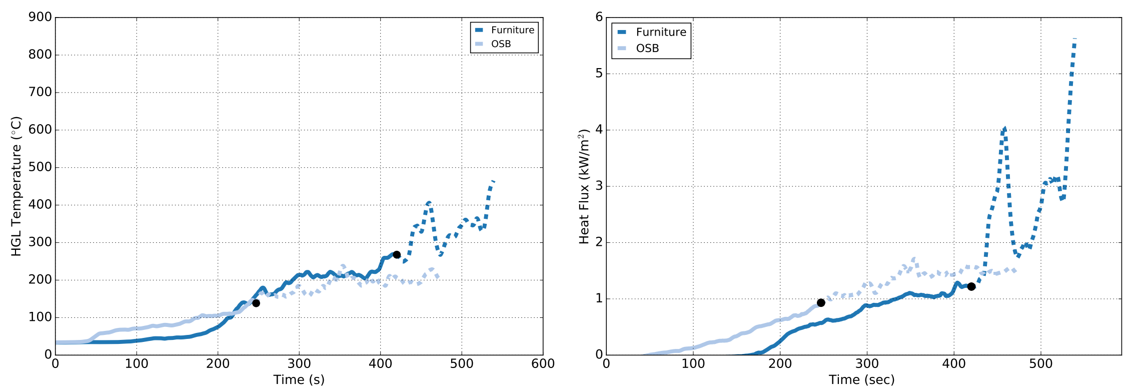
before beginning to decay as the fire runs out of fuel. Figure 5.11 shows the hot gas layer temperatures and floor heat flux histories for Experiments 1 and 8. So, there was a significant increase in both hot gas layer temperature and floor heat flux in the fire room, although these increases were not nearly as severe as those noted in the furnished room fires. As a result of the smaller magnitude of this increase, the increase in thermal conditions in rooms adjacent to the fire room was not as noticeable as the increase within the fire room itself. Figure 5.12 shows the heat flux and hot gas layer temperature in Room 202 for the near vent experiments. Inspection of the heat flux graph indicates that the increase in heat flux from just over 1 kW/m^2 to 4 kW/m^2 that occurs as the fire room flashes over is not noted in the OSB fire, where the heat flux steadily increases from just below 1 kW/m^2 to just over $1.5 kW/m^2$. Thus, ventilation results in an increase in temperatures and heat flux readings in the fire room, although this increase is not as severe as that noted in the furnished room experiments, especially as the distance from the fire room is increased.



(a) Room 201 Hot Gas Layer Temperature

(b) Room 201 Floor Heat Flux

Figure 5.11: Hot Gas Layer Temperature and Heat Flux for Near Ventilation in Furniture and OSB. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.



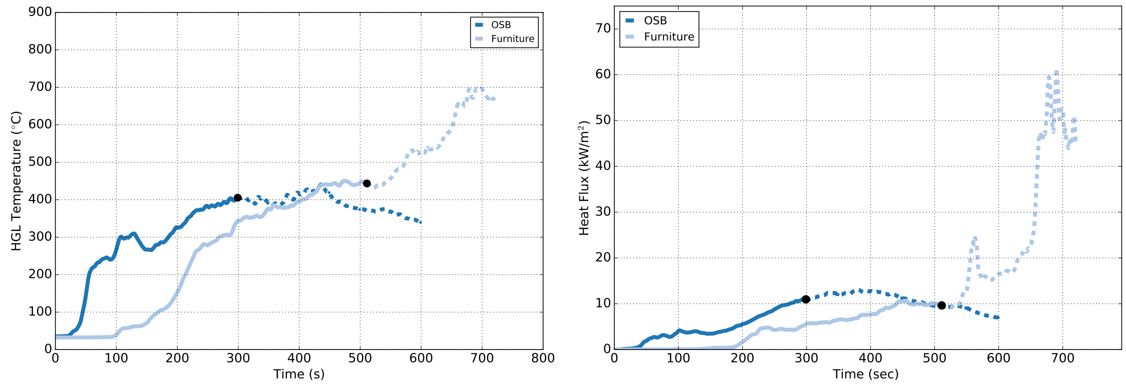
(a) Room 202 Hot Gas Layer Temperature

(b) Room 202 Floor Heat Flux

Figure 5.12: Hot Gas Layer Temperature and Heat Flux for Near Ventilation in Furniture and OSB. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

In Experiment 4, where the ventilation was performed remotely from the OSB fire, there was not as significant of an increase in heat flux following ventilation. Following the ventilation of the Room 204 window and the front door, the fire room heat fluxes continue to increase following ventilation, but there is no rapid increase, as was observed in Experiment 8. Rather, there is a steady increase from a flux of 10 kW/m^2 at the time of ventilation to just over 13 kW/m^2 at the peak. Following this peak, the fire room heat flux decreased steadily until the end of the test. A similar trend was noted in the hot gas layer temperatures for Experiment 4. Following ventilation, the hot gas layer temperatures remained steady around 400 °C, before decreasing in a manner similar to the heat flux. The temperatures and heat fluxes in Experiment 5 followed a separate trend. The heat flux and hot gas layer temperatures for Experiments 4 and 5 are shown in Figure 5.13. Following ventilation, the hot gas layers steadily increased, though not as rapidly as in the fire room ventilation case. The heat flux behavior following ventilation showed an increase to a local peak before increasing to flashover conditions.

The primary difference between these two fuels is the absence of a single, well mixed layer of unburned fuel in the OSB. The oxygen concentration profiles listed in Figure 4.2 for the OSB fires indicate that two distinct zones exist for the duration of the experiment: an upper layer with elevated temperatures and reduced oxygen concentrations and a lower layer with lower temperatures and oxygen concentrations close to ambient levels. In the furnished room fires, this two zone phenomenon is not observed, as evidenced by the low oxygen concentrations and high temperatures at the 2 ft. level. When fresh air is introduced to the oxygen-depleted, fuel-rich gas



(a) Room 201 Hot Gas Layer Temperature

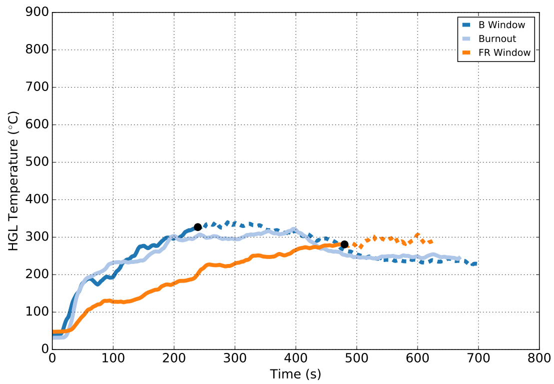
(b) Room 201 Floor Heat Flux

Figure 5.13: Hot Gas Layer Temperature and Heat Flux for Near Ventilation in Furniture and OSB. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

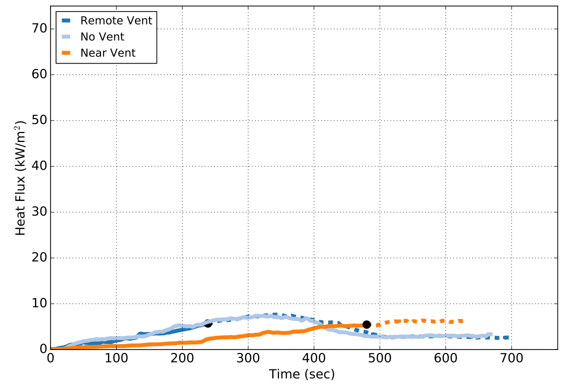
layer in the furnished room fires, burning is able to occur within the gas layer itself. Recall in Table 5.2, where the amount of air required for stoichiometric combustion was roughly 3 times the volume of the building. The incomplete combustion that results from this discrepancy means that not all of the gaseous fuel is able to burn, forming a fuel-rich thermal layer that is deficient in oxygen. Once oxygen is provided via ventilation, there is still a great deal of fuel mass to burn.

This fuel rich thermal layer was not observed in the OSB experiments, which is consistent with the analysis in table 5.2, since the mass of fuel, and the amount of air required for complete combustion of this fuel, was not as high as the furnished fuel package. The gas layer in the OSB fires is not hot enough to burn, except for areas close to the fuel package itself. There are several possible reasons that the gas layer is not hot enough to burn. One possible reason is the thick, concrete walls of the training building, which have different thermal properties than the gypsum board found on residential surfaces. Concrete takes considerably more energy to heat up than gypsum board, as evidenced by the thermal inertia values: 2.8 $(kW/m^2K)^2s$ for concrete compared to $0.18 (kW/m^2K)^2s$ for gypsum board [37]. As the hot gases travel from the fire room along the ceiling, they lose energy to the concrete block walls and ceiling, resulting in a cooler hot gas layer in areas remote from the fire room. In addition to the cooling action of the concrete block, as air travels from the ventilation point to the seat of the fire, mixing occurs between the fresh air and the hot gases closer to the ceiling. In addition to entraining oxygen into the layer, this also cools these hotter gases. The cooling that occurs to the gas layer by a combination of heat removal via the concrete surfaces and mixing with the cool, fresh air results in a gas layer that is not hot enough to burn, as was noted in the furnished room fires. This cooler gas layer explains the dampened response to ventilation noted in the near ventilation case, and the lack of any significant fire growth in the remote ventilation case.

The pallets and straw exhibited negligible growth following both methods of ventilation. Figure 5.14 shows the hot gas layer temperatures and heat flux histories for the pallets and straw experiments. Inspection of these charts reveals that the burnout experiment and the remote ventilation experiment behaved quite similarly, even following remote ventilation. The similarity of the temperature-time profiles would indicate that the remote ventilation had no significant impact on the temperatures or heat flux in the fire room. It would follow that the temperatures and heat fluxes elsewhere in the training building would be similarly unimpacted. The fire in Experiment 7 developed differently than the other two pallets and straw fires, not reaching as high of an initial peak. Inspection of the temperature and heat flux profiles, however, indicates that the heat flux curve is nearly unimpacted, and the hot gas layer temperature merely fluctuates between the time of ventilation and the end of the experiment. The absence of change resulting from ventilation is likely because the gas layer is not hot enough to sustain combustion, but also because the rate at which the pallets and straw fuel package produces products of combustion is less than the rate that smoke and hot gases are being exhausted from the building. Additionally, recall that the natural ventilation openings within the structure provide a continuous source of fresh air to the fire, even when all ventilation openings are closed. The pallets and straw fuel package required the least amount of air for complete combustion (Table 5.2, and since the fire already has a continuous supply of air, the additional ventilation provided by the window did not have as drastic of an effect towards increasing combustion as it would for the other two fuels, which have a higher synthetic content. These synthetic materials, such as polyurethane, have a higher oxygen demand, as discussed previously.



(a) Room 201 Hot Gas Layer Temperature



(b) Room 201 Floor Heat Flux

Figure 5.14: Hot Gas Layer Temperature and Heat Flux for Pallets and Straw. Solid lines represents data prior to ventilation, which is denoted by a black dot. Post-ventilation data is denoted by a dotted line of the same color as the corresponding solid line.

The response of the fire to ventilation is an important aspect when considering the fidelity with which training fuels simulate the fire dynamics created in a furnished room fire common of a residential house. Fires using furniture as a fuel tend to exhibit increases in temperatures and heat flux in areas close to the fire room. The closer the ventilation to the seat of the fire, the more rapid the response. In both the remote ventilation case and the fire room ventilation case the fire room eventually transitioned to flashover. The reason for this behavior can be attributed both to the high synthetic content of the fuel and the larger total mass of fuel in the fuel package. The high oxygen demand of the fuel results in underventilated conditions, and growth following the introduction of additional oxygen.

The OSB fires demonstrated a limited increase in temperatures and heat fluxes corresponding with ventilation for the near ventilation case. In the remote ventilation case, however, there was no noticeable growth that occurred following remote ventilation. It is likely that the hot gas layer temperature decreased below the point where additional oxygen would have enabled burning. The pallets and straw exhibited negligible growth following ventilation. Although the oxygen concentrations of the OSB fuel package indicated that two zones were maintained throughout the experiment, it is possible that the evacuation of smoke that occurred as a result of fire room window ventilation allowed for a local increase in burning, which may have been responsible for the increase in thermal conditions. Thus, it can be said that the OSB fuel package had some dependence on ventilation. The fire behavior of the pallets and straw fires, on the other hand, was largely unaffected by ventilation, meaning that this fire could be considered fuel limited. The difference between these two training fuels helps to illustrate the importance of fuel control when conducting a training evolution. The addition of fuel can result not only in more severe thermal conditions in the period leading up to ventilation, but the rapid deterioration of conditions following ventilation.

It is important that the ventilation response of these fuels be put into context when firefighters use them in training evolutions. If ventilation is incorporated into a training scenario, it is important that instructors clarify that, in the absence of suppression, ventilation actions may have a more severe impact on fireground conditions and firefighter tenability on the actual fireground with modern fuels than they did in the training scenario using training fuels. Instructors may consider using additional fuel packages that could be ignited in a timeframe consistent with the growth of a fire in a furnished room to artificially simulate an increase in thermal conditions due to ventilation. In such scenarios, it is important that instructors recognize that the goal of the training simulation should not be to create conditions consistent with a furnished room fire, but rather to replicate the response of the fire to firefighters' actions on the fireground. Such a balance between fidelity and safety is considered in the following section.

5.2 Safety

Utech's thermal operating classes were used to quantify the severity of the thermal conditions present in the training fires and the furniture fires. In order to quantify the most serious conditions that were present in each experiment, the peak temperature at the 3 ft. level and the heat flux value that was recorded at the same time as this peak temperature were used to classify the thermal hazard according to Utech's method. It should be noted that Utech's thermal operating classes display radiant flux along the x-axis, but in these experiments, the heat flux gauges measured total heat flux. Since the heat flux was measured at the floor level, away from any gas flows of significant temperature, it is reasonable to assume that this total heat flux measurement is a good approximation of the radiative flux.

Figure 5.15 shows where the peak values for each of the furniture, OSB, and pallets and straw experiments fell on Utech's chart. The furniture fires peaks fell well within the Emergency operating condition, which is consistent with expectations, since each of the furnished room experiments exhibited conditions consistent with flashover. The OSB fires each fell towards the lower end of the emergency operating range. Note that for one of the OSB tests, Experiment 4, the temperature criteria was within the range of Emergency conditions, while the heat flux criteria met that of ordinary operating conditions. While, technically, this peak falls into an intermediate area between the ordinary and emergency operating classes. Each of the pallets and straw fires were within the ordinary operating range.

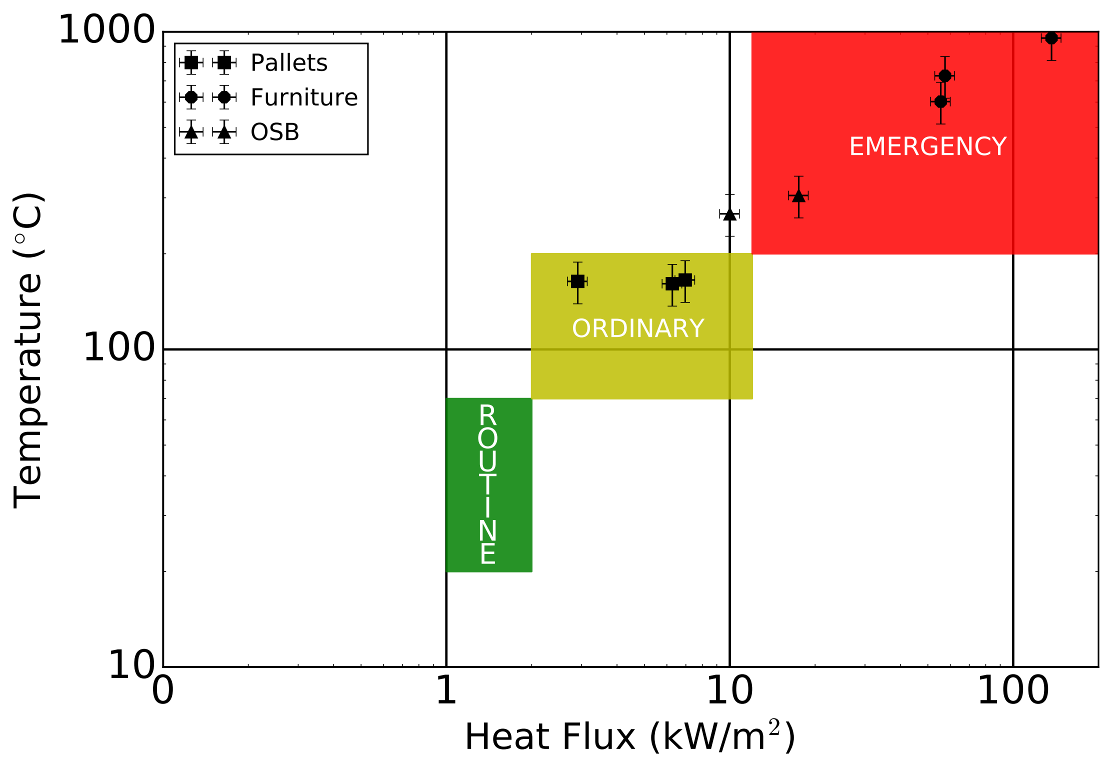


Figure 5.15: Thermal Operating Conditions in Fire Room (Room 201)

This illustrates an important difference between the two training fuels: OSB and pallets and straw. Since the operating class for the pallets and straw is within ordinary operating conditions, instructors and stokers would be able to operate in the fire room for periods of time without risking thermal injury. This would allow these firefighters to maintain the fuel package or instruct students as necessary. Additionally, it allows a certain margin of error for newer recruits, who would be able to be in the fire room if they became lost or disoriented, or if they were unable to apply water to the fire. In the OSB training fires, however, the fire room is only habitable for mere seconds before firefighters risk compromising their turnout gear. Further, the margin of error for students is not as great as in the pallets and straw fire. If a recruit firefighter were to make a mistake or become disoriented, they may find themselves in a more hazardous environment. While the peak thermal conditions are not nearly as severe in the OSB fire as they are in the furnished room fires, they do fall within the same operating class, meaning that there is a similarly high level of risk.

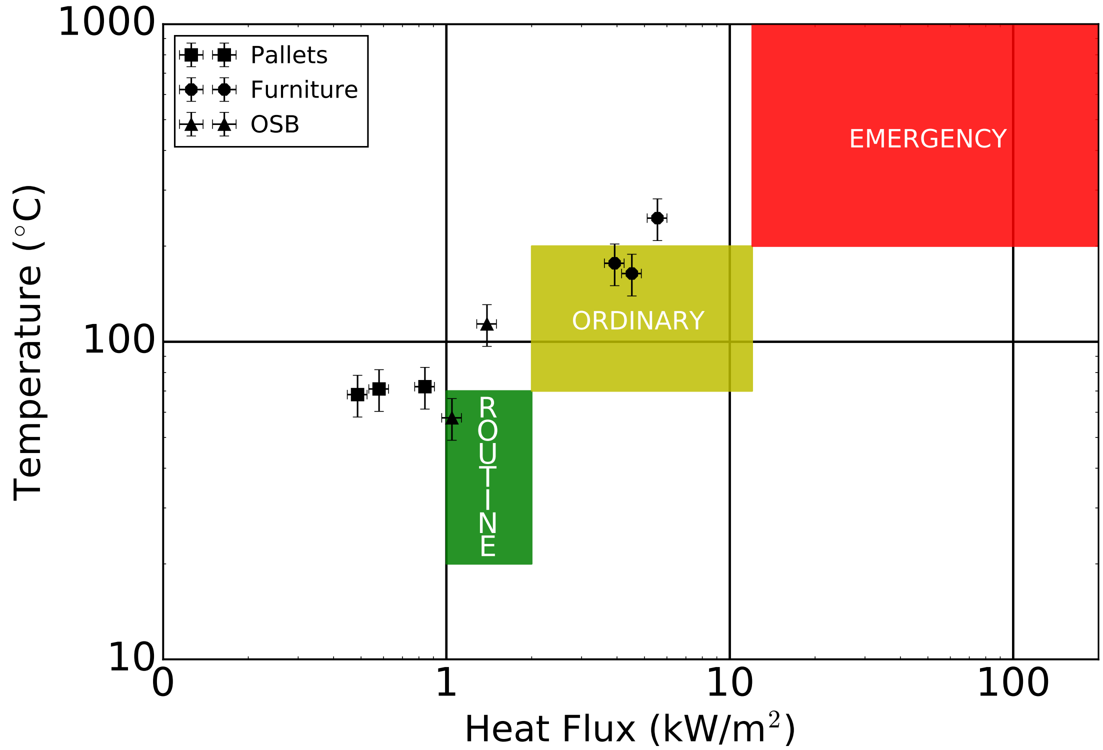
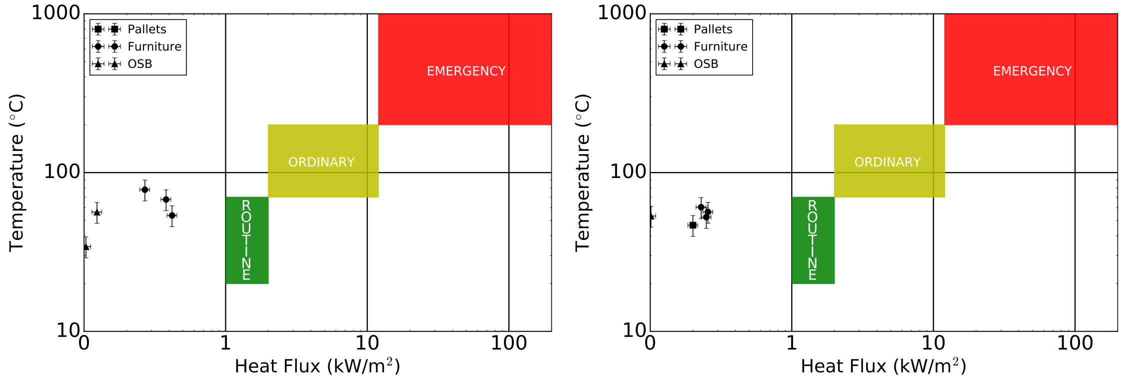


Figure 5.16: Thermal Operating Conditions in Room 202

As the distance from the fire room increases, the hazard classification similarly decreases. Figure 5.16 shows the thermal operating class that the peak temperature and the heat flux recorded at this time fall into for each experiment. In this room, two of the three furnished room fires fall within the ordinary operating range, and the third falls within the heat flux criteria for the normal operating range while exceeding the temperature criteria. This is consistent with the definition of that class, that is, the conditions in a room adjacent to one that is flashing over. The OSB fires exhibited less severe thermal conditions than those in the furniture fires, with one experiment falling into the routine operating class and the other falling between the routine and ordinary classes. All of the pallets and straw fires had heat fluxes less than 1 kW/m^2 at the time that the peak temperature was recorded, although the temperatures at the 3 ft. level were within routine operating criteria. Although the peak temperatures were similar between the pallets and the OSB fuels, the heat flux values were quite different, indicating that radiative heat flux form the gas layer has more of an effect on thermal conditions in the OSB tests than in the pallets. So, the furnished room experiments and OSB were the only experiments where thermal conditions were elevated, whereas the pallets and straw experiments exhibited much more moderate temperatures in the approach to the fire room.

This highlights another important distinction between training fires and real fires. In the training fires, and the pallets and straw tests in particular, thermal conditions were not elevated until in or near the fire room. Thus, a student in full PPE would be able to approach and enter the fire room before significant thermal conditions would be noted. The lack of significant thermal conditions in areas remote from the fire room is further evidenced in Figure 5.17, which shows where the peak temperatures and their corresponding heat fluxes fall on Figure 2.1. Even for the furnished fires, where flashover conditions were present only a few rooms over, the heat fluxes recorded in these locations is quite negligible, and the temperatures are very low. Studies [5, 6] have indicated that this significant reduction in thermal conditions on the approach to the fire is not noted in residential fires, particularly when the firefighters are working in the flow path of the fire. Thus, the situation where firefighters are exposed to negligible thermal conditions during training is unlikely to be replicated on the fire ground. It is important that students appreciate this difference, so as not to breed complacency when responding to fires in real structures.



(a) Room 203

(b) Room 204

Figure 5.17: Thermal Operating Conditions Rooms 203 and 204

One important element that is missing from the thermal operating classes proposed by Utech is the time component. The peak temperatures in Figures 5.15-5.17 offer a mere snapshot in time of the thermal conditions that instructors and students would be exposed to. Consider Figure 5.18, which shows the heat flux and temperature data plotted at the time of ventilation, and at intervals of 30s, 60s, 90s, and 120s. The grouping for the pallets and straw experiments is concentrated in this region over the time interval, indicating that the pallets and straw fire remains stagnant in the ordinary region in the two minutes following ventilation. In the furnished room, the thermal conditions within the fire room are already in the emergency operating range at the time of ventilation, although the severity of conditions increases following ventilation, remaining in the emergency operating zone for the two minute period. In the OSB experiment, the ordinary conditions were in the ordinary operating range at the time of ventilation. Over the next two minutes, the severity of these conditions increase into the emergency operating range.

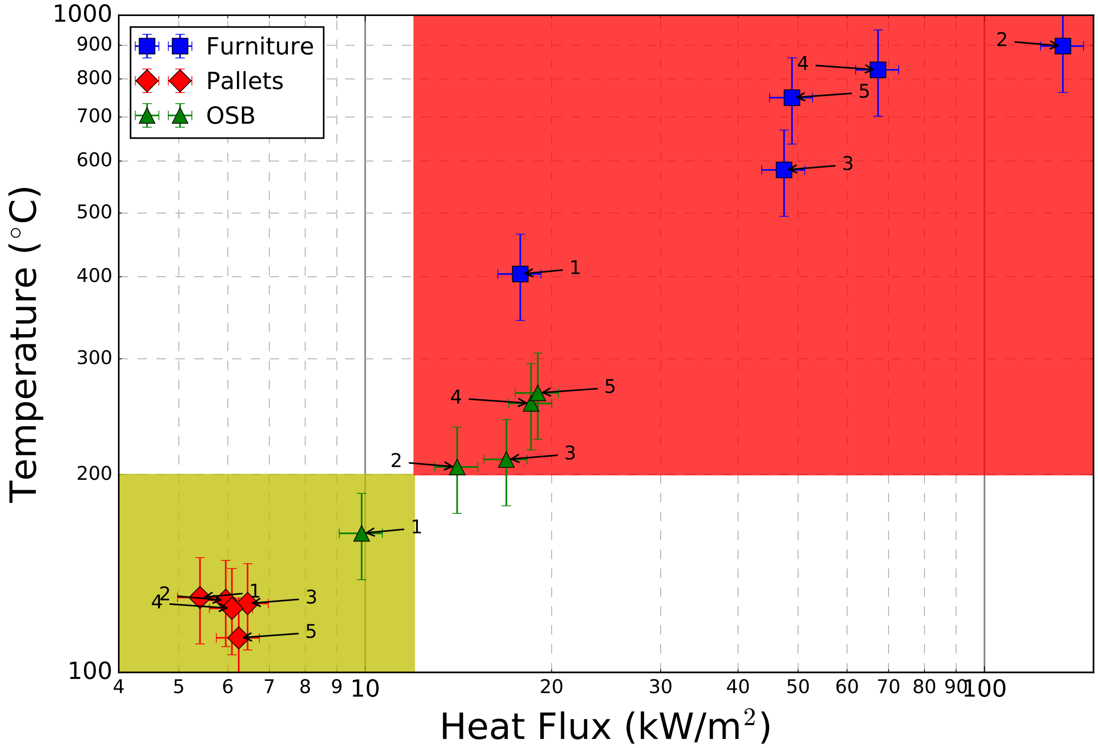


Figure 5.18: Ventilation Response of Fire for Near Vent Experiments. Points are labeled 1,2,3,4, and 5, corresponding to the temperature and heat flux at 0 s, 30 s, 60 s,90 s, and 120 s, respectively.

A similar trend can be seen in the remote ventilation experiments, as seen in Figure 5.19. Just as in the near ventilation case, the pallets and straw experiments maintain a tight grouping for the 150 seconds following ventilation. At the time of ventilation, the conditions in the furnished room met the heat flux criteria for the ordinary operating range and the temperature criteria for the emergency operating range. After the first 60 seconds, the temperature crossed into the emergency operating range. The OSB exhibited a similar trend, starting in the ordinary operating class at the time of ventilation, before increasing into the emergency operating class until the heat flux began to decrease, bringing the thermal conditions into the area where the temperature exceeds ordinary operating conditions, but the heat flux meets these criteria. Note also that, while the OSB thermal conditions do increase, they increase at a more consistent rate than was noted in the near ventilation scenario. This further illustrates the difference between the near ventilation experiment and the remote ventilation experiment for the OSB.

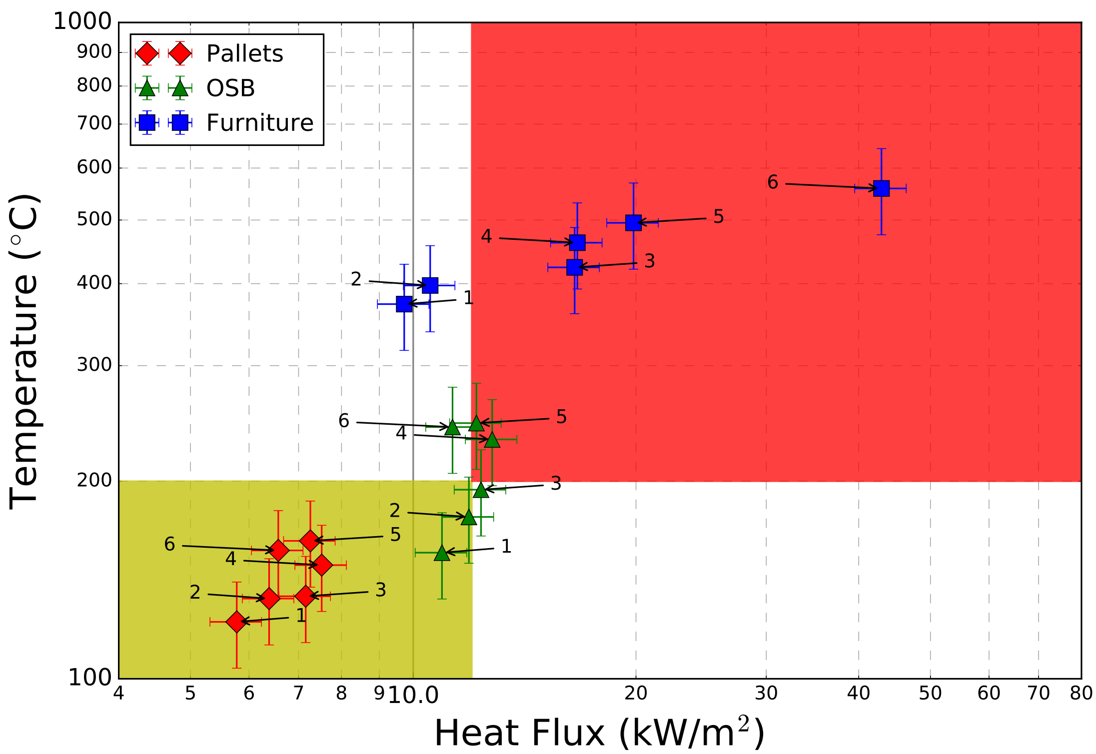


Figure 5.19: Ventilation Response of Fire for Near Vent Experiments. Points are labeled 1, 2, 3, 4, and 5, corresponding to the temperature and heat flux at 0s, 30s, 60s, 90s, 120s, and 150s, respectively.

Figures 5.18 and 5.19 demonstrate the importance of the time component of evaluating the thermal response to firefighters, and highlight the differences in ventilation between the three fuel packages. The pallets and straw thermal conditions are steady following ventilation, so students or instructors would feel little change from the action. An increase in the severity of thermal conditions was noted in the OSB experiments, but this change was more gradual than the rapid change that was observed in the furnished rooms. Consider the near ventilation case. If OSB was used as a fuel, students and instructors would be exposed to a gradual increase in conditions from roughly 160°C and 10 kW/m^2 at the time of ventilation to 265°C and 19 kW/m^2 after two minutes. In the furnished room, thermal conditions increased from 403°C and 17 kW/m^2 at the time of ventilation to 900°C and 130 kW/m^2 after only 30 seconds. The increase in conditions in the furnished room is larger in magnitude and occurs over a shorter span of time, meaning that firefighters would have less time to react to the worsening conditions. Although the conditions noted in the OSB tests were severe, they are within the limits of PPE worn by firefighters [24,25] for short durations. The experiments conducted by Mensch et al. [26] indicated that the time to SCBA facepiece failure is dependent on the severity of the thermal exposure. Thus, although the thermal conditions in the OSB experiments and the furnished room experiments are in the emergency operating range, and conditions within these rooms could eventually cause failure of a firefighter's PPE, the length of time that a firefighter would have until their PPE was compromised may vary significantly.

The variations in thermal conditions that occur over the duration of the experiments, as well as the time of exposure highlight an important gap in understanding in the thermal operating class method of evaluating firefighter safety. In defining each class, Utech lists a reference time. The ordinary operating class is defined as being an area where firefighters could operate for the entire 20 or 30 minute duration of a fire incident [23]. He describes the emergency operating class as one in which a firefighter can survive in for only a few minutes before suffering burn injuries. As discussed in the Chapter 2, while firefighter PPE has improved since the time that Utech proposed the thermal operating classes, the thresholds that he defined still correspond to the critical temperatures and heat fluxes of various pieces of firefighter PPE. Furthermore, Figures 5.18 and 5.19 demonstrate that in fires with modern furnishings, the thermal operating class is not stagnant for the duration of a fire. In order to fully capture the thermal risk to firefighters during a training evolution, the analysis would not only have to consider the peak heat flux and peak temperature, but rather a fractional approach, similar to toxicity calculations, where the time history of the temperature and heat flux could be considered. Thus, the most appropriate way of characterizing a firefighter's thermal exposure would be to develop a time-dose relationship, which would consider the transient nature of the thermal conditions at firefighter operating height, the time-dependent transfer of heat through turnout gear, and the threshold of burns to the skin, or the failure of various pieces of PPE.

Chapter 6: Summary

The goal of fire service training is to prepare students for the conditions and challenges that they face on the fireground. In the constantly evolving modern fire environment, with more tightly sealed homes and higher-heat release rate fuels, it is important that training fuels keep up with the trend. Pallets and straw, a commonly used training fuel in training academies across the United States, are more representative of a legacy fuel than a modern one. Recognizing this gap, some instructors have begun to incorporate engineered wood products into their training fuel packages. While use of these fuels can create fire dynamics more similar to furnished rooms, they can also create more severe thermal hazards. In order to better understand the fire dynamics of these training fires, a series of experiments was conducted in an effort to evaluate the fidelity and safety of two training fuels, pallets and OSB, and compare these training fuels to modern combustibles similar to those that would be encountered on the residential fireground.

6.1 Pallets and Straw as Training Fuel

Pallets and straw remains a common training fuel for live fire evolutions in the United States. The low cost and ease of procurement of these materials makes them ideal for stockpile and use in training burns. The results of these experiments, however, indicated that both the physical and functional fidelity of the pallets and straw fires were quite low. The temperatures and heat fluxes outside of the fire room remained much lower than those noted in the furnished room fires. Additionally, the decrease in oxygen concentrations at the 2 ft. level that was noted in the furnished room experiments was not noted in the pallets and straw experiments. Further, when ventilation was initiated, the fire did not increase in size in any appreciable way, indicating that the burning was likely fuel limited rather than ventilation limited. The peak thermal conditions noted in the pallets and straw tests fell into the ordinary operating class, meaning that a firefighter in full PPE would be protected for short exposures. Because of these less severe thermal conditions, instructors may elect to use pallets and straw as a training fuel for evolutions involving newer recruits, such as a Firefighter I class. This would allow these students to practice firefighting skills while being exposed to heat and smoke while maintaining a margin of error. Regardless of the evolution, it is essential that instructors using pallets and straw as a fuel emphasize the differences between a pallets and straw training fire and a residential fire with modern combustibles, so that bad behaviors developed on the training ground are not carried over to the fireground.

6.2 Use of Synthetic Materials as Training Fuels

NFPA 1403 specifically prohibits the use of synthetic fuels such as treated wood products, rubber, plastic, polyurethane foam, upholstered furniture, and chemically treated straw. Some instructors, however, have begun to incorporate engineered wood products, like oriented strand board (OSB), into their training burns in an effort to create conditions that are more consistent with a furnished fire. The results of these experiments indicated that the training fires using OSB as a fuel exhibited a limited degree of functional fidelity to the furnished room fires. In the near ventilation case, temperatures and heat fluxes within the fire room increased following ventilation in a trend consistent with the furniture fires. Nevertheless, the same response was not noted in the remote ventilation case. Since the gas layer in the OSB experiments was not hot enough to sustain burning, and the compact fuel package minimized the effect of radiative heating from the gas layer, the same magnitude of growth noted in the furnished rooms was not observed in the OSB fires.

The OSB fuel package exhibited a higher degree of functional fidelity than the pallets and straw and the thermal environment created was also more severe, particularly in the fire room. The peak thermal conditions crossed into the emergency operating class, meaning that firefighters could only be exposed for a short duration before suffering burn injuries or death. This is a marked contrast to the pallets and straw, where instructors or students could operate with a relative degree of safety in the fire room for longer periods of time. Thus, if OSB is to be used as a training fuel, it is important that instructors and students maintain a safe distance from the fire room while a hoseline is in place. Training facilities may want to consider implementing different policies for OSB evolutions compared to pallets and straw evolutions. Furthermore, OSB training burns should be reserved for students with more experience, whose more solid foundation in firefighting skills would allow them to benefit from the more realistic, albeit more hazardous, training without putting themselves in unnecessary harm.

6.3 Physical vs. Functional Fidelity

Fisher [14] describes how the mentality of some fire service instructors is to pack as much fuel as possible into an evolution in order to create a fire that is as realistic as possible. NFPA 1403 recommends against this practice, indicating that the fuel load should only be large enough to create a fire of the desired size [7]. This discrepancy highlight's Hartin's discussion of functional versus physical fidelity. In this instance, the instructors that Fisher describes are advocating for physical fidelity, that is, creating a fire that is feels the same as an actual residential fire. By doing this, instructors are doing their students a disservice, because they may be creating both conditions that are hazardous to the students while not accurately replicating a residential fire. Rather, it is important that instructors focus on maximizing the functional fidelity of a training burn. This facilitates a productive training experience for students while limiting the fire size to a safe, manageable fuel load in accordance with NFPA 1403.

6.4 Future Work

These experiments examined the fire behavior of three different fuels in concrete training buildings. Concrete training buildings such as the one in this series of experiments are only one of many types of containers that firefighters conduct training in. The behavior of various fuels in these containers should be studied and compared to their behavior in concrete buildings. The discussion of this study briefly touched upon the effect of wall linings on heat loss from the hot gas layer remote from the fire room. This effect would be useful to understand, not only for training fires, but for fires in all types of compartments.

When considering the safety of firefighters in a thermal environment, the method of Utech [23] was used. This method considers the thermal threat to the firefighter in terms of two components: a radiant component and a convective component. The convective component is approximated by the temperature in the area that the firefighter is operating, but this neglects an important facet: the gas velocity. Higher gas velocities would result in higher convective heat transfer coefficients and a higher convective heat flux. Furthermore, the thermal threat of the firefighter should not be considered as an isolated peak event, but rather as a fractional dose, dependent on both the thermal load and the time of exposure. Thus, future work should focus on better evaluating the thermal hazard posed to firefighters not only in a training environment, but on the fireground as well.

Appendix A: Training Fire Fuel Weights

Experiment	**Pallet Weights (kg)**	**Straw Weight (kg)**	**Total OSB Weight (kg)**
3	n.r.	n.r.	-
4	18.0, 20.1, 19.1	n.r	n.r
6	18.1, 17.1, 16.9	n.r.	-
7	17.4, 20.4 15.8	14.7	-
8	18.6, 19.1, 19.5	13.9	42.3

Appendix A: Thermal Conditions Remote from Fire Room

Table A.1: Peak Heat Fluxes Remote From Fire Room

Experiment	Room 202		Room 203		Room 204	
	Pre-Vent	**Post-Vent**	**Pre-Vent**	**Post-Vent**	**Pre-Vent**	**Post-Vent**
1	1.34	5.57	0.16	0.47	0.11	0.40
2	4.72	-	0.46	-	0.37	-
3	0.63	0.96	0.04	0.09	0	0.23
4	0.88	1.17	0.06	0.12	0	0.08
5	1.82	4.73	0.18	0.46	0.14	0.46
6	0.71	-	0.07	-	0.08	-
7	0.53	0.79	0.03	0.04	0	0.02
8	0.97	1.86	0.06	0.17	0.02	0.18

Table A.2: Peak 3 ft. Temperatures Remote From Fire Room

Experiment	Room 202		Room 203		Room 204	
	Pre-Vent	**Post-Vent**	**Pre-Vent**	**Post-Vent**	**Pre-Vent**	**Post-Vent**
1	105.3	245.0	45.0	78.1	43.7	60.5
2	176.6	-	53.7	-	52.4	-
3	55.1	72.2	31.1	42.6	30.2	46.7
4	46.9	57.6	31.9	34.2	30.7	31.6
5	100.4	164.0	43.4	67.7	46.1	56.5
6	74.5	-	39.9	-	39.4	-
7	55.1	71.0	33.1	45.4	32.3	41.3
8	67.3	113.8	33.9	56.4	33.3	53.3

Appendix A: Hot Gas Layer Interface Heights

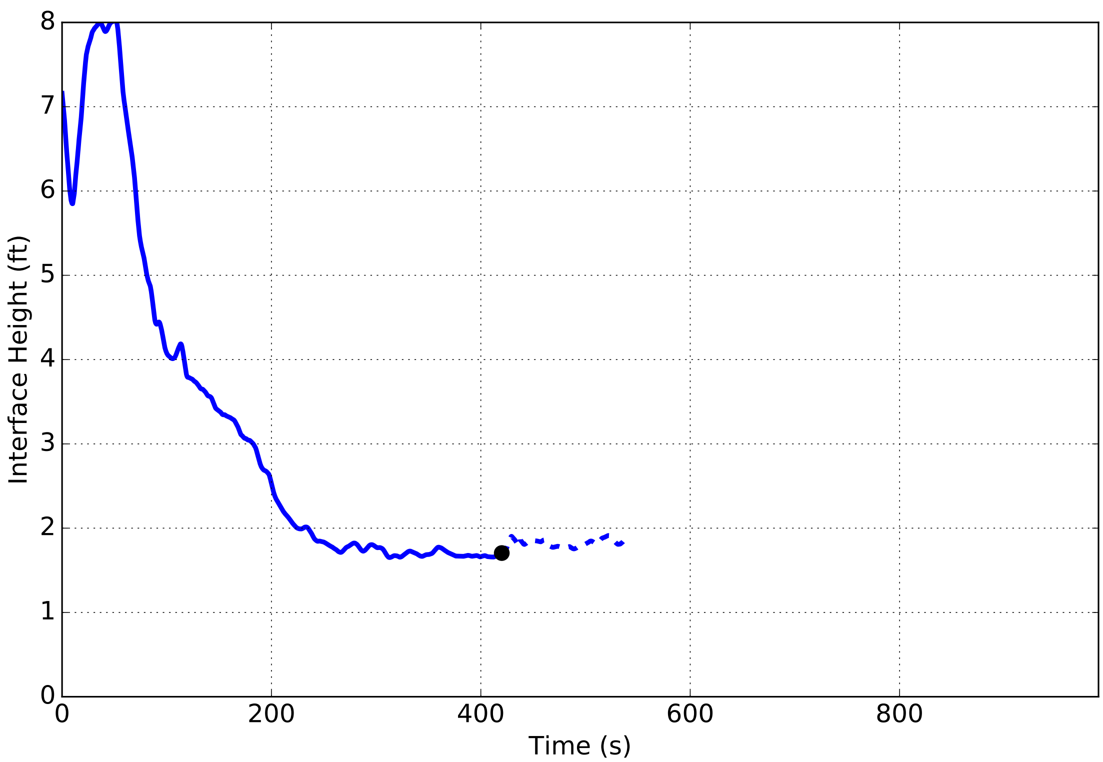


Figure A.1: Upper Gas Layer Interface for Experiment 1

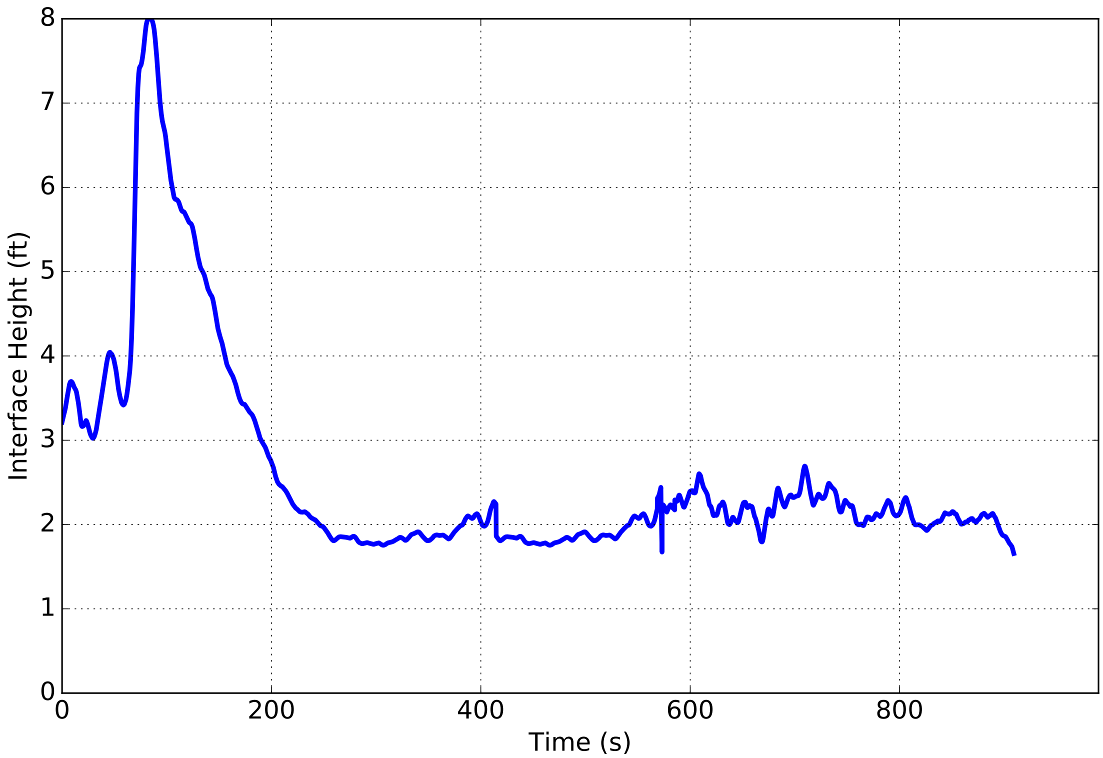


Figure A.2: Upper Gas Layer Interface for Experiment 2

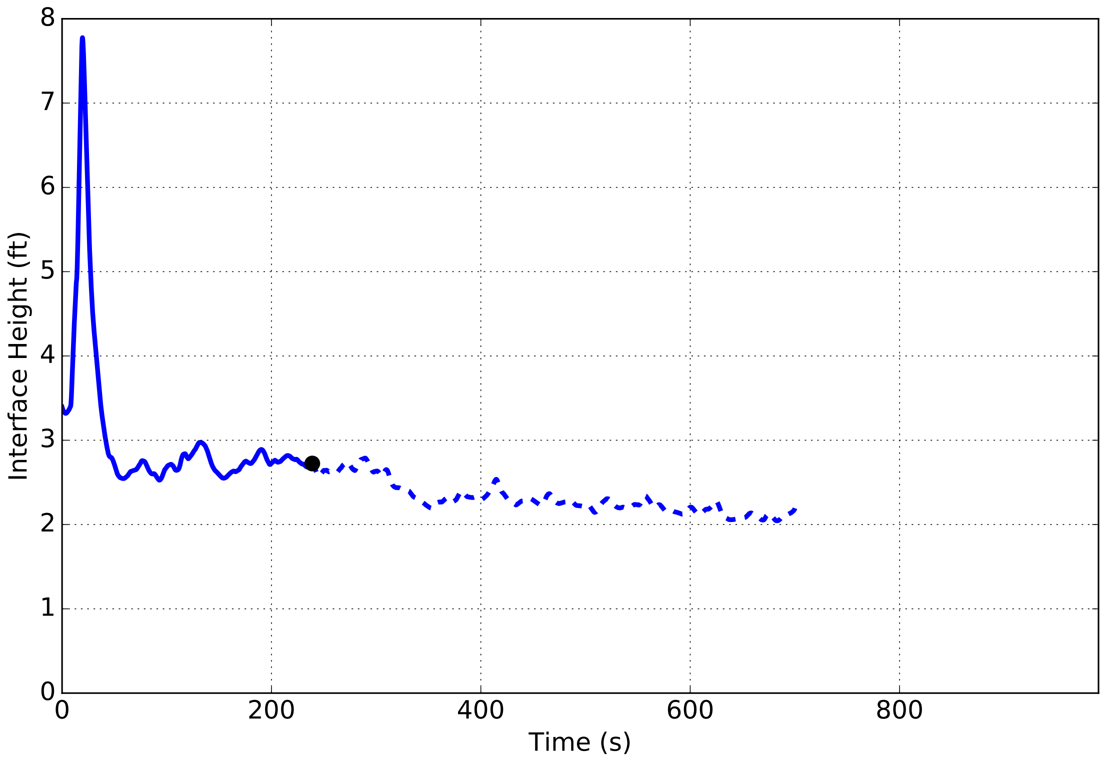


Figure A.3: Upper Gas Layer Interface for Experiment 3

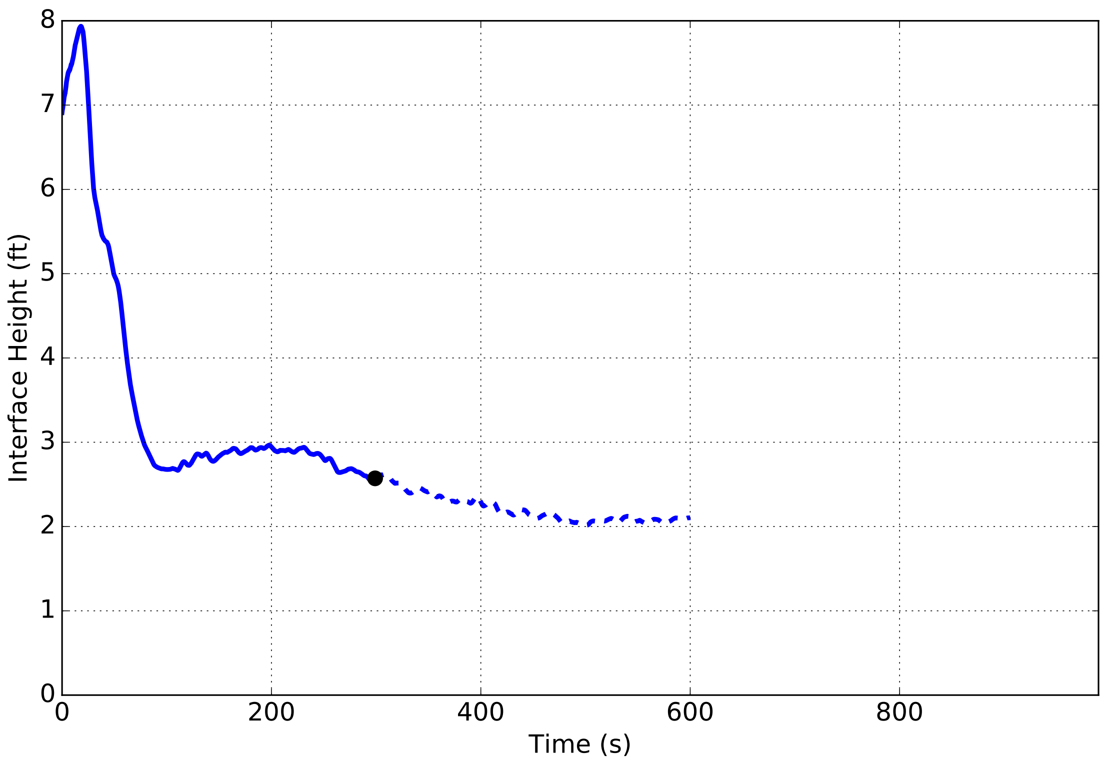


Figure A.4: Upper Gas Layer Interface for Experiment 4

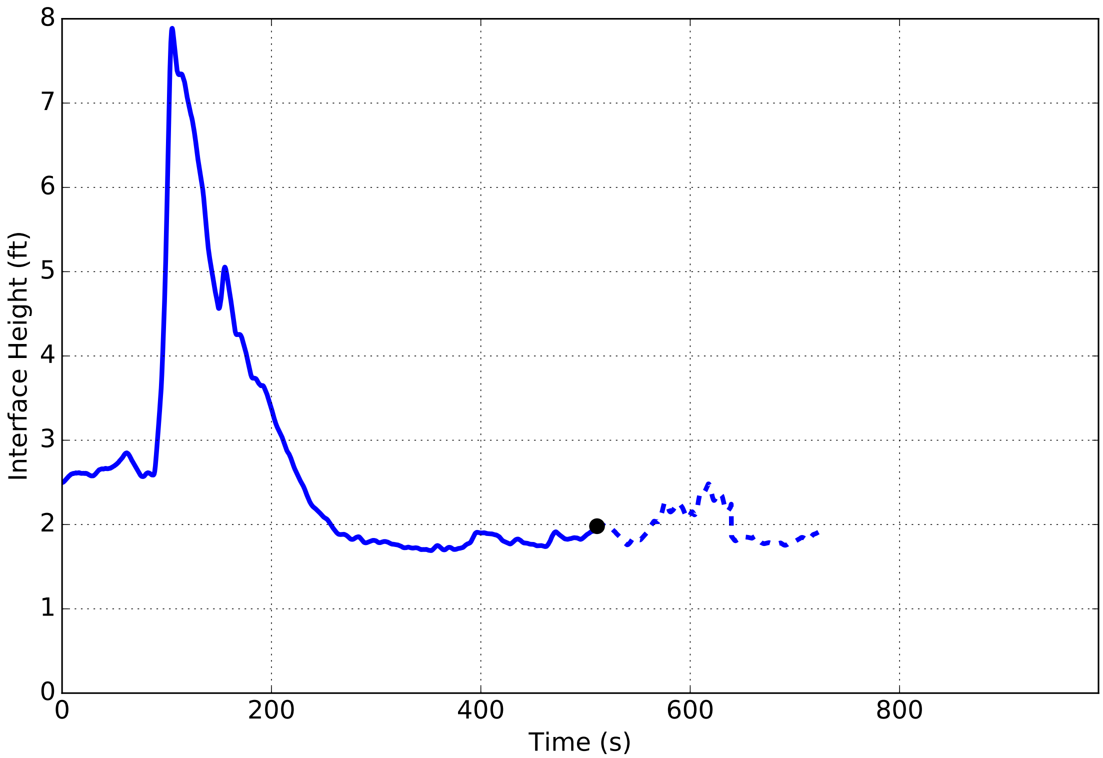


Figure A.5: Upper Gas Layer Interface for Experiment 5

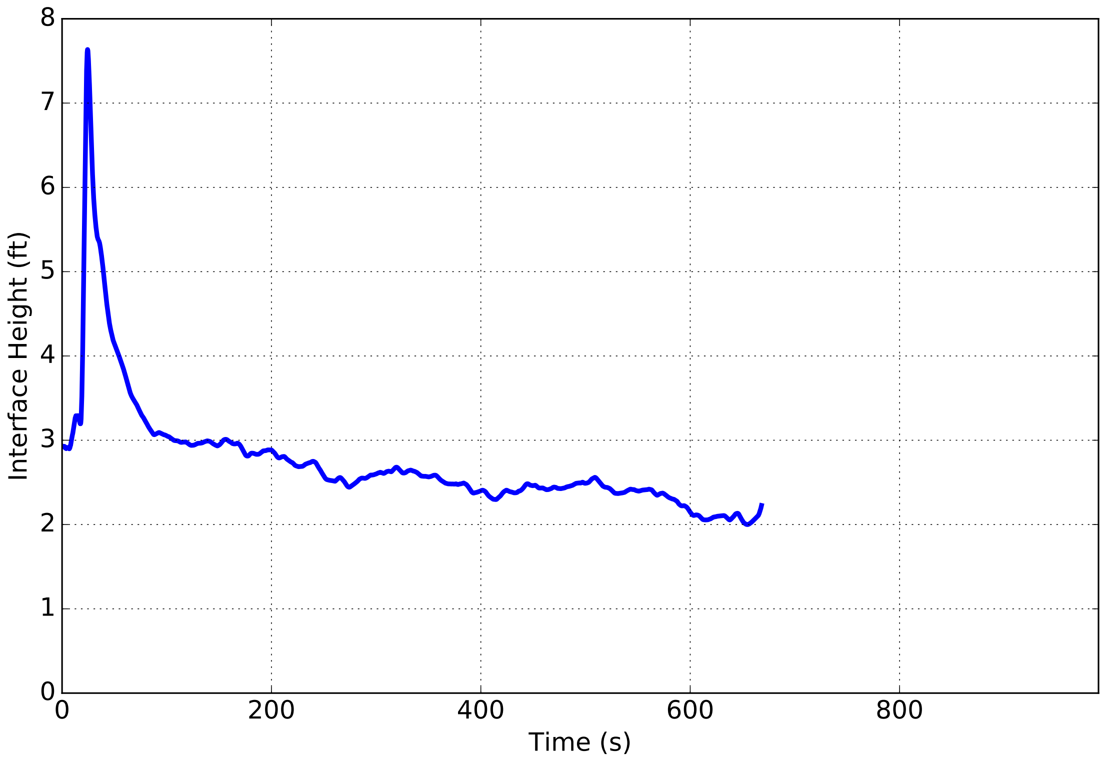


Figure A.6: Upper Gas Layer Interface for Experiment 6

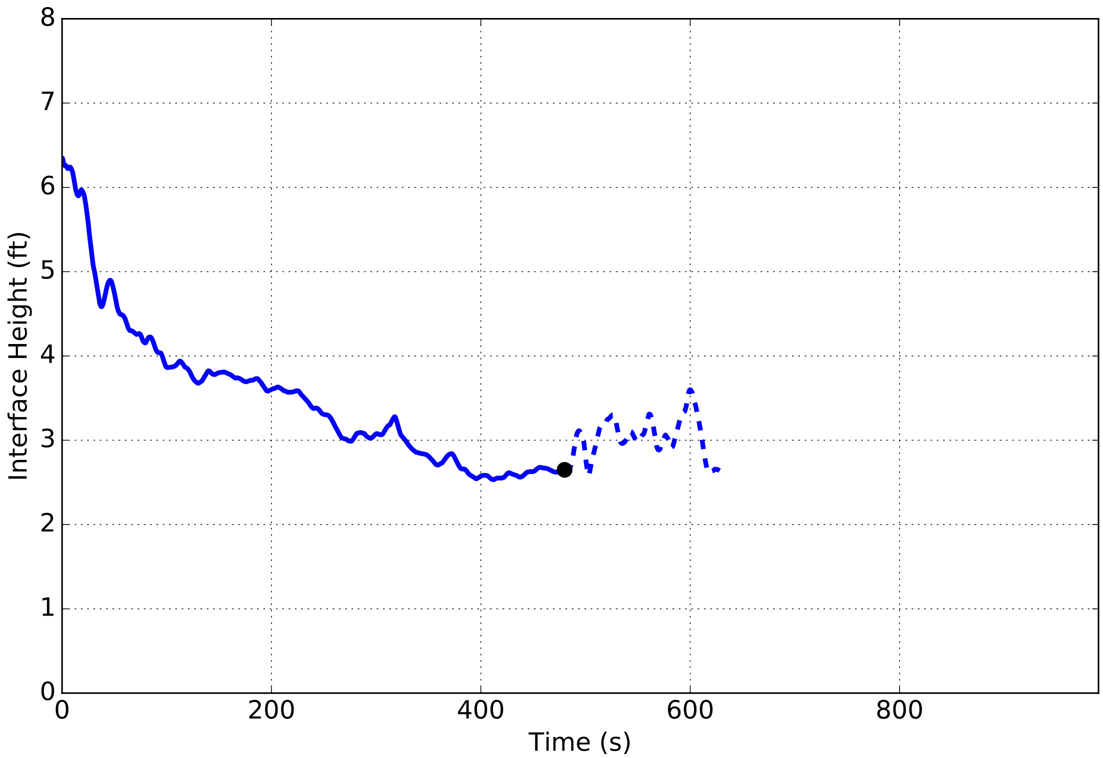


Figure A.7: Upper Gas Layer Interface for Experiment 7

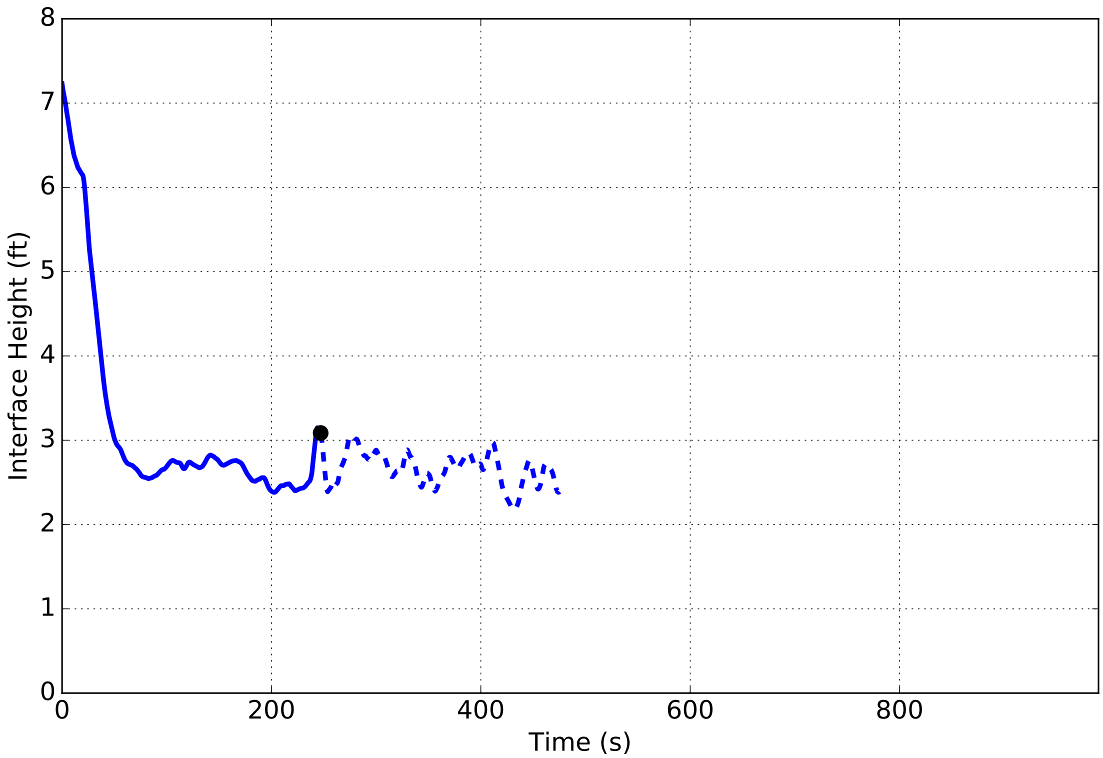


Figure A.8: Upper Gas Layer Interface for Experiment 8

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