Study of the Fire Service Training Environment: Safety, Fidelity, and Exposure

Acquired Structures

Keith Stakes
Joseph Willi

UL Firefighter Safety Research Institute
Columbia, MD 21045

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UL Firefighter Safety Research Institute
Stephen Kerber, Director

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List of Abbreviations

AFG	Assistance to Firefighters Grant
BDP	Bi-directional Probe
CAD	Computer-Aided Design
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DHS	U.S. Department of Homeland Security
ESTC	Emergency Services Training Center
FEMA	Federal Emergency Management Agency
HRR	Heat Release Rate
IC	Incident Command
IDLH	Immediately Dangerous to Life and Health
ISFSI	International Society of Fire Service Instructors
LODD	Line of Duty Death
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute of Standards and Technology
NFPA	National Fire Protection Association
OSB	Oriented Strand Board
O_2	Oxygen
PPA	Positive Pressure Attack
PPE	Personal Protective Equipment
PPV	Positive Pressure Ventilation
RIT	Rapid Intervention Team
TC	Thermocouple
UL	Underwriters Laboratories
UL FSRI	UL Firefighter Safety Research Institute
VES	Vent Enter Search
VEIS	Vent Enter Isolate Search

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Fire Service Technical Panel

Name	Affiliation
Derek Alkonis	Los Angeles County Fire Department
Brian Arnold	Oklahoma City Fire Department
Charles Bailey	Montgomery County (MD) Fire & Rescue Services
John Ceriello	Fire Department of the City of New York
Sean DeCrane	Cleveland Fire Department (Ret.)
James Dominik	Northeastern Illinois Public Safety Training Academy
Michael Cox	Maryland Fire and Rescue Institute
Kenny Fent	National Institute for Occupational Safety and Health
Michael Gagliano	Seattle Fire Department (Ret.)
Sean Gray	Cobb County Fire Department
Bobby Halton	Fire Engineering Magazine
Todd Harms	Sacramento Fire Department
Ed Hartin	Central Whidbey Island Fire & Rescue
George Healy	Fire Department of the City of New York
Gavin Horn	University of Illinois Fire Service Institute
David Rhodes	Atlanta Fire Department
John Cunningham	Alabama Fire College; North American Fire Training Directors
Ken Richards	Old Mystic Fire Department; NFPA 1403
Erich Roden	Milwaukee Fire Department; Fire Rescue Magazine
Tim Sendelbach	Firehouse Magazine (Ret.)
Dan Shaw	Fairfax County Fire Rescue; NFPA 1403
Denise Smith	Skidmore College
Jens Stiegel	Frankfurt am Main Fire & Rescue Services
Stefan Svensson	Lund University, Department of Fire Safety Engineering
Adam Thiel	Philadelphia Fire Department
Peter Van Dorpe	Algonquin-Lake in the Hills Fire Department
Devon Wells	International Society of Fire Service Instructors

Abstract

Previous UL FSRI led research projects have focused on examining the fire environment with regards to current building construction methods, synthetic fuel loading, and best-practices in firefighting strategies and tactics. More than 50 experiments have been previously conducted utilizing furniture to produce vent-limited fire conditions, replicating the residential fire environment, and studying the methods of horizontal ventilation, vertical ventilation, and positive pressure attack [1–3]. Tactical considerations generated from the research are intended to provide fire departments with information to evaluate their standard operating procedures and make improvements, if necessary, to increase the safety and effectiveness of firefighting crews. Unfortunately, there still exists a long standing disconnect between live-fire training and the fireground as evident by continued line of duty injury and death investigations that point directly to a lack of realistic yet safe training, which highlights a continued misunderstanding of fire dynamics within structures.

The main objective of the *Study of the Fire Service Training Environment: Safety, Fidelity, and Exposure* is to evaluate training methods and fuel packages in several different structures commonly used across the fire service to provide and highlight considerations to increase both safety and fidelity. This report is focused on the evaluation of live-fire training in acquired structures. A full scale structure was constructed using a similar floor plan as in the research projects for horizontal ventilation, vertical ventilation, and positive pressure attack to provide a comparison between the modern fire environment and the training ground. The structure was instrumented which allowed for the quantification of fire behavior, the impact of various ventilation tactics, and provided the ability to directly compare these experiments with the previous research.

Twelve full scale fire experiments were conducted within the test structure using two common training fuel packages: 1) pallets, and 2) pallets and oriented strand board (OSB). To compare the training fuels to modern furnishings, the experiments conducted were designed to replicate both fire and ventilation location as well as event timing to the previous research. Horizontal ventilation, vertical ventilation, and positive pressure attack methods were tested, examining the proximity of the vent location to the fire (near vs. far). Each ventilation configuration in this series was tested twice with one of the two training fuel loads.

The quantification of the differences between modern furnishings and wood-based training fuel loads and the impact of different ventilation tactics is documented through a detailed comparison to the tactical fireground considerations from the previous research studies. The experiments were compared to identify how the type of fuel used in acquired structures impacts the safety and fidelity of live-fire training. The comparisons in this report characterized initial fire growth, the propensity for the fire to become ventilation limited, the fires response to ventilation, and peak thermal exposure to students and instructors. Comparisons examined components of both functional and physical fidelity. Video footage was used to assess the visual cues, a component of the fire environment that is often difficult to replicate in training due to fuel load restrictions. The thermal environment within the structure was compared between fuel packages with regards to the potential tenability for both students and instructors.

1 Introduction

Firefighting research within UL FSRI to date has focused primarily on quantifying the modern fire environment in order to provide the fire service with tactical considerations to improve both fireground safety as well as overall effectiveness of firefighting crews. Fire service ventilation and suppression tactics have been examined to improve the understanding of how fireground actions result in changing fire behavior within a structure, its potential impact to firefighter safety, and victim survivability. Other research projects have focused on emerging trends with building construction practices in addition to new technology such as photovoltaic arrays. The findings from these research projects have had positive impacts, helping guide the fire service to modify strategies and tactics on the fireground and adjust training methods accordingly as they adapt to the changing fire environment. However, this increased understanding of fire behavior has continued to raise questions of how to teach these principles to those operating on the fireground from the newest recruit firefighter to the senior chief officers in charge of incident command. These questions highlight challenges which still exist in terms of linking the tactical fireground considerations to training.

Those involved with training often ask what level of fidelity is needed to develop the knowledge and subsequent skills necessary for a safe and effective operation on the fireground. There are critical learning outcomes which directly relate to fidelity including: 1) developing an understanding of fire development in a compartment, 2) dynamic risk assessment regarding recognizing critical fire behavior indicators, 3) selecting appropriate fire suppression tactics, 4) developing competence and confidence when operating in a hazardous and immediately dangerous to life and health (IDLH) environment, 5) developing skill in nozzle operation and technique, and 6) evaluating the effect of tactical operations on victim survivability and incident mitigation. Taking all of these concepts into consideration leaves instructors with the lingering questions of how to create fidelity within the constraints of *NFPA 1403: Standard on Live Fire Training Evolutions* during interactive or demonstrative hands-on, live-fire training evolutions.

Traditionally, firefighter training methods revolve around including both conceptual (classroom) learning and hands-on evolutions. Through UL FSRI generated on-line learning modules, UL FSRI technical and fire service summary reports, in-person presentations, and access to content through social media; fire department instructors and firefighters have been exposed to the latest information as the research continues. As such, many fire departments have adapted their recruit and in-service training to incorporate these changes as they arise. Unfortunately, it is not as easy to incorporate these changes practically on the training ground. Many training buildings and fire behavior props, when used according to current standards and common construction practices, will not create a fire environment that is representative of the changes seen on the fireground. Due to past training involved line of duty injuries and deaths, the current training standards enforce restrictions on fuel type and quantity as well as the structure construction to ensure the safety of the student and instructor. Fire departments also may place restrictions on the fuel arrangement and structure configuration in attempts to limit the risk during live-fire training evolutions. These limitations may lead to differences in fire behavior between the training ground and fireground which can mislead students as to what conditions in an actual structure fire may look like. It is imperative that fire department instructors are able to provide the correct context to the students so that proper lessons are learned while providing a safe and predictable training environment.

Historically, the fire service has relied upon initial recruit training to prepare firefighters for what they may face on actual incidents with the anticipation that on-the-job training will fill in the gaps. Fire department instructors ensure that the student develops a basic conceptual understanding in addition to a practical skill set that can be expanded upon with field experience. Firefighters, regardless of rank and riding assignment, are expected to make critical decisions on the fireground that influence the ever-changing fire environment and the direct safety of themselves as well as any potential trapped occupants. Realistic training allows the student to build an internal catalog of conceptual knowledge and practical skill sets combined with experience. This experience provides the student with the ability to recognize visual cues and conditions on the fireground to assist in rapid decision making, improving overall safety and effectiveness. The number of fires today in one and two family homes is 50% less than in the early 1980's [4]. This decrease in residential fires has led to a decrease in the ability to gain fireground experience and fill in the gaps that current training is unable to fill. This highlights the importance of hands-on evolutions and live-fire training that minimize risk and maximize fidelity.

Training on fireground strategies and tactics emphasizes a hands-on learning approach, but creating ventilation-limited, post-flashover fires can be very dangerous and impact the lifespan of current training buildings. Several fire service line of duty deaths and injuries have been the result of attempts to replicate the modern fire environment by incorporating synthetic fuels while not anticipating the potential fire dynamics. Fires involving synthetic fuels are characterized by rapid fire growth, which has caught instructors familiar with natural fuels off guard, and has ultimately led to the loss of firefighters' lives [5, 6]. Compartment fires in the training environment differ from those encountered during real incidents due to compartment construction and configuration, fuel characteristics, ventilation profiles, and time scale. Traditionally, firefighters have been placed into training buildings constructed of concrete with leaky openings, where a pile of natural fuels such as pallets and/or straw are placed in a room and ignited. The fire grows to a fuel limited state and direct suppression is limited in order to achieve multiple repetitions of crews building practical skills such as advancing hose-lines with live-fire. The structure creates an unrealistic fire environment for several very important reasons: 1) the building is concrete because it needs to withstand many fires over many years to be economical and safe (not the same response as a typical gypsum and wood-framed building), 2) the building is leaky because all openings need to be easily opened from inside and outside, hoses cannot get stuck under doors for safety reasons, and water needs to drain easily, and 3) pallets and straw are used because they are readily available, relatively cheap, and create a fairly predictable fire with predictable heat release rates. The resulting fuel limited fire does not experience growth or similar response to ventilation like a fire involving synthetic furnishings. Recent research has shown that the modern fire environment is commonly ventilation limited due to construction practices that seal houses tightly for energy conservation and the synthetic materials utilized in furnishings that produce high heat release rates [7].

The potential exists for students to observe and internalize inaccurate concepts. Some examples include ventilation always leads to cooling and a more rapid return to improved conditions (better visibility and lower heat), ventilation reduces the chance of flashover, firefighters always have the ability to enter the fire room before flowing water, firefighters should limit water usage as steam generation may be a concern for both firefighters and victims, and ventilation limited conditions are only hazardous due to decreased visibility.

Without instructors who have a good working knowledge of fire dynamics and how firefighting strategies and tactics will impact those fire dynamics, these inaccurate messages may be internalize by the students and lead to a larger disconnect between conceptual understanding of the material and the practical application through live-fire training. This disconnect can lead to misapplication during decision making on the fireground when firefighters are presented with visual cues and fire dynamics that they have never experienced. This forces the firefighter to draw back to the basic principles and skill sets derived during live-fire training, placing them at a risk for injury or death based on the inconsistencies between the training and reality.

While structural characteristics and ventilation within the training buildings differ from residential homes, another significant difference lies in the type, quantity, and configuration of fuel allowed for training. The National Fire Protection Association (NFPA) 1403 Standard on Live-Fire Training [8] is fairly explicit regarding fuel characteristics and loading for live-fire training evolutions. The fuel loading in most residential and commercial occupancies is considerably higher than what is typically used in training. Some firefighters believe the only way to have realistic training is to conduct live-fire evolutions in acquired structures with synthetic fuel loads; however, this is not in compliance with NFPA 1403 Standard on Live Fire Training. The standard states that fuels utilized in live-fire training evolutions shall only be wood products. Pressure-treated wood, rubber, plastic, polyurethane foam, upholstered furniture, and chemically treated or pesticide-treated straw or hay shall not be used. Unidentified materials, such as debris found in or around the structure or prop that could burn in unanticipated ways, react violently, or create environmental or health hazards, shall not be used. Additionally, fuel materials should only be used in amounts necessary to create the desired fire size for the evolution while limiting the quantity to avoid uncontrolled flashover or backdraft.

Since the fire service cannot train in realistic structures with synthetic fuel loads, the fidelity of training is of even more importance. Fidelity is the degree of exactness with which something is copied or reproduced. Fire training can involve a wide range of simulations, from the use of photos and video for size-up and decision making evolutions, non-fire exercises involving repetitive tactical skills such as deploying a hose line, small scale props to show fire behavior, single and multi-compartment props for either live-fire evolutions or search techniques, burn buildings, and acquired structures. Each provides differing degrees of fidelity. One approach to examine fidelity during fire training is to consider two components: physical fidelity and functional fidelity. Physical fidelity is the extent to which the simulation looks and feels real. Functional fidelity is based on the extent to which the simulation works and reacts realistically. In firefighting simulations, key elements of physical fidelity will likely include fire behavior indicators such as the fire condition and ventilation profile. Important aspects of functional fidelity would include the characteristics of doors and windows (e.g., opening mechanism), hose and nozzles, and influence of tactics such as hose stream application on fire behavior. Replicating conditions encountered during emergency operations using an acquired structure would likely provide the most realistic context and correspondingly the greatest risk to participants. Because of this, fire department instructors often attempt to utilize an acquired structure and challenge the limitations of NFPA 1403 with regards to fuel type, loading, and configuration in attempt to gain the most realism within live-fire training.

This portion of the Fire Service Training study highlights the conditions faced within acquired structures while abiding to the current training standard. These conditions are compared to conditions faced within the same structure, utilizing synthetic furnishings as the fuel loading with the same ventilation profile and suppression tactics. With an improved understanding of how acquired structure fires behave, fire department instructors can build training curriculum that not only improves the fidelity but also improves the overall safety of the live-fire evolution.

1.1 Objectives

The objective of this project is to improve the fire service knowledge of fire dynamics and the impact of various tactics on potential victims, firefighter safety, and the overall fire environment within the structure through a better understanding of how the safety, fidelity, and exposure of the training ground relates to the fireground. This project is intended to expand upon the previous research studies conducted regarding ventilation: *Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction*, *Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes*, and *Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices* [1–3]. The changes between the modern fire environment and the training ground are analyzed to lead to improved hands-on training for the fire service.

As mentioned above, this study focused on live-fire training in acquired structures, and is just one component of the project titled *Study of the Fire Service Training Environment: Safety, Fidelity, and Exposure*. The goals and objectives for the project in its entirety include the following:

- Improve firefighter safety by increasing knowledge of fire behavior.
- Bridge the gap between fire dynamics knowledge and the utilization of training buildings and training props for hands-on training.
- Characterize fuels commonly used in training and compare them to fuels found in the residential fire environment for both burning characteristics and potential firefighter exposure.
- Better understand the concepts of fuel and ventilation limited fires and research how they can be visually taught during hands-on fire training.
- Provide firefighters and fire instructors with an interactive training program that will provide context and a connection between the training environment and the fireground.

1.2 Limitations & Scope

This study looked at the impact of utilizing training fuels, currently allowed within NFPA 1403, in acquired structures. Due to the significant number of variables in live-fire training, limitations exist in the ability to evaluate them all. The variables selected for evaluation were chosen to bound the problem to an analysis of ventilation tactics and provide insight into how training fuel packages compare to modern furnishings within a similar structure. These variables included the structure construction, size, and configuration, fuel loading, fire department arrival time, fire location, ventilation profile, and the timing and execution of ventilation tactics.

The test structure was designed by a residential architectural company to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms. A common ceiling height of 8.0 ft (2.4 m) was located throughout. The wood frame, type V, structure totaled approximately 1200 ft^2 (111.5 m^2) and included three bedrooms, a living room, dining room, and kitchen with breakfast area. Intervention times were based on fire department personnel arriving after the fire became ventilation limited. As such, the structure was closed with no exterior ventilation openings until this time. The sequence and timing of additional interventions was based upon the previous research studies to which these experiments were compared; horizontal ventilation, vertical ventilation, and positive pressure attack.

Two types of fuel packages were used in this study: 1) pallets and 2) pallets and oriented strand board (OSB) to match the previous research on training fires completed in other portions of this study. The heat release rate and burn characteristics for the specific fuel packages have been quantified in the portion of this project titled *Study of the Fire Service Training Environment: Safety, Fidelity, and Exposure - Training Fuel Packages* [9]. It should be noted that the analysis is based off of these two fuel packages which are both wood-based, but are of different mass. Some of the conclusions drawn may show differences between the two fuel packages, but this is likely due to the additional mass and not the composition of the additional fuel as evident in the training fuel packages study. The fire location within the structure was once again chosen based on the previous experiments for comparison. By bounding these variables from the beginning and controlling these test conditions during the experiment, it was possible to evaluate the fire behavior within the structure and provide a direct comparison to synthetic fuel loading from the previous experiments.

Suppression, both as a tactic and equipment utilized, was not a focus of this study. The main intent of the study was to quantify the fire behavior of training fuels in acquired structures to provide a comparison to the modern fire environment and assist in evaluating live-fire training. These experiments were also a representation of room and contents fires that one would typically encounter during live-fire training evolutions. These fires did not penetrate the walls, voids, or attic space within the structure. Additionally, these experiments took place outdoors and had the potential to experience environmental conditions such as wind, rain, temperature, pressure, and humidity based on the location and time of year that they were conducted. All attempts were made to ensure the experiments were conducted at times with little to no wind or other adverse weather conditions that could have impacted results.

2 Literature Review

The current standard from the National Fire Protection Association (NFPA) which regulates firefighter training is NFPA 1403: Standard on Live Fire Training Evolutions. It outlines the requirements for live-fire evolutions in acquired and fixed facility training structures. The document discusses the responsibilities of 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 document advises that the fuel load should be limited to mitigate the potential for uncontrolled backdraft or flashover. NFPA 1403 additionally makes several specific recommendations for acquired structure training evolutions. 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 did not discuss the importance of fire dynamics concepts [8].

NFPA 1403 was developed in response to a live-fire training incident 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 since 1982 where firefighters have been killed or injured during live-fire evolutions in acquired structures. Investigations into these incidents has revealed that the recommendations from NFPA 1403 were not followed. The National Institute of Occupational Safety and Health (NIOSH) further investigated several of these incidents:

Maryland, 2007 In a 2007 incident, a probationary firefighter was killed during a training evolution in a vacant end-of-the-row townhouse in Maryland. The scenario used approximately 12 wooden pallets, 11 bales of excelsior, and miscellaneous trash from the structure (tires, mattresses, foam rubber chair, tree branches, etc.) 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 high heat conditions, two of the participants exited the structure through a window. The victim reached the window, but was unable to get the lower half of her body through 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* [10].

Florida, 2002 Two career firefighters were killed during 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 carpet padding, hollow core wood doors, and carpeting were not removed, and thus contributed to the fuel load. The victims entered the structure and performed a primary search of the building. Shortly after, the primary attack crew followed the search and rescue crew into the structure with a charged hoseline. After searching the living room, the two victims made their way to the fire room as smoke conditions intensified. Approximately three and a half minutes after the search team had entered the structure, the exterior ventilation firefighter was ordered to break out the window of the fire room. This caused the fire in the room to rapidly transition to flashover. The interior attack company, positioned outside the fire room doorway, began to apply water in short-flow increments into the room. 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. The investigation identified the fuel load contents 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 [11].

Madrzykowski [5] investigated the above incident by recreating the fire room and two adjacent spaces and evaluating the thermal conditions produced by five different combinations of fuel load and ventilation conditions. Flashover conditions were generated in all five scenarios. Furthermore, during every experiment, temperatures measured 1.0 ft (0.3 m) above the floor of the fire room exceeded 500 °F (260 °C), and heat fluxes measured 3.3 ft (1.0 m) above the floor exceeded 20 kW/m^2, indicating conditions in the fire room were untenable for a firefighter in full PPE. An additional experiment examined the peak HRR of the pallets and straw and found it to be 2.8 MW [5]. The author compared this HRR to the theoretical HRR required for flashover in the room and discovered that the measured peak HRR exceed the theoretical HRR required for flashover.

New York, 2001 In another LODD incident, a New York volunteer firefighter was killed during a simulated "mayday" scenario, where he and another firefighter were acting as the simulated victims. The victim had very little training prior to the incident and had never previously worn a self-contained breathing apparatus (SCBA) under live-fire conditions. The training was conducted in a vacant two story duplex. The scenario called for two firefighters 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 the foam mattress of a sleeper chair after the ignition firefighter experienced difficulty with igniting the barrel. 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 of doing so, lost his gloves, received burns to his hands, and was forced to exit out 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 who was removed from the structure and the ignition firefighter who jumped from the second floor were flown to a regional burn center. The post-incident 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* [12].

Delaware, 2000 A volunteer lieutenant was killed during live-fire training in an acquired structure in Delaware. The lieutenant was killed after all of the scenarios of the day had been completed, and the structure was being prepared for burn-down. Miscellaneous debris was doused in accelerant, placed in the attic, and ignited with a flare. The lieutenant remained behind to ensure that the fire was progressing. When he failed to exit, the other firefighters on the scene attempted to rescue him, but were unsuccessful. He was removed from the structure after the building collapsed, and pronounced dead on the scene. The investigation highlighted the use of improper ventilation and flammable liquid accelerants as contributing factors in this scenario [13].

Incidents such as those described above highlight the debate within the fire service about balancing safety requirements, such as those recommended in *NFPA 1403*, with fire training that prepares recruits for actual firefighting. Many articles published in fire service trade magazines have focused on various aspects of live-fire training, namely, the usefulness of conducting training that adheres to the guidelines of *NFPA 1403*, methods and techniques to implement during exercises to increase the effectiveness of the training, and limitations of *NFPA 1403*-compliant training to replicate conditions experienced on the fireground.

One such article, written by Greg Fisher, highlights the importance of following *NFPA 1403* during live-fire training [14]. 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 composition 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 larger than what students are comfortable with may cause students to panic, invalidating the training. When constructing a fuel package with pallets, Fisher highlights geometry as an important factor. He states that the pallets and straw should be arranged in a corner as close to the ceiling as possible. Such an arrangement allows for the fire to rapidly reach a fully-developed stage and mimic the behavior of a room-and-contents fire. Fisher adds that it is important to watch for window and ceiling failure during the training evolution, as these events could cause unwanted changes in fire behavior. Lastly, he stresses that students' safety and comfort level should be prime considerations in the orchestration of acquired structure training burns [14].

In an article published by *Fire Engineering*, Kriss Garcia and Reinhard Kauffmann [15] present some of the challenges associated with conducting acquired structure training. The authors describe an instance in which many hours of work were performed 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 training structure prop, 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 they claim it will generate enough energy to bring the room to flashover [15].

In January 2012, four firefighters were injured during a training evolution that utilized a gypsum training prop similar to that described above. The incident resulted in the dismissal of several chief officers. The 1500 ft^2 (140 m^2) prop was being used to conduct a demonstration of positive pressure fire attack. Several fuel packages were placed throughout the structure. During the first evolution, the fire grew and developed until window coverings of the fire room were removed, and a positive pressure ventilation fan was turned on to expedite the ventilation process. Seconds later, rapidly devolving conditions on the interior forced four students and an instructor to evacuate through windows on opposite ends of the prop, and subsequent training evolutions were canceled [16].

Forest Reeder presents the debate within the fire service about balancing the need for realistic training with safety requirements in his article [17]. Reeder highlights some of the complaints that are frequently voiced against the standard. Some instructors are frustrated that *NFPA 1403* prohibits what they consider to be more realistic training evolutions: ones 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 smoke and high heat conditions frequently encountered on the fireground. Reeder emphasizes that the safety requirements seen by some 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 fireground. Reeder maintains that control and pre-planning are important facets of a successful live-fire training evolution [17].

3 Experimental Configuration

The full-scale experiments described within this report were conducted in a purpose-built residential structure on the grounds of the Delaware County Emergency Services Training Center (ESTC) in Sharon Hill, Pennsylvania. The structure was previously utilized in the summer of 2017 for the Department of Homeland Security (DHS) project on Understanding and Fighting Basement Fires, a joint project between the UL FSRI and the International Society of Fire Service Instructors (ISFSI) [18]. The experiments for this study were conducted in the spring of 2018 and included twelve experiments with two different fuel packages, three different fire locations, three different types of fire service ventilation, and six different ventilation profiles. The following sections describe the construction and configuration of the structure, the instrumentation details and locations, and fuel loads used during the experiments.

3.1 Experimental Structure

While this test fixture was originally purpose-built for research experiments, the construction of the structure fell within the definition and usage of an acquired structure for live-fire training. According to the NFPA 1403 standard, a live-fire training structure is a structure specifically designed for conducting live-fire training evolutions on a repetitive basis. Live-fire training structures include those built of conventional building materials such as concrete, masonry, and steel as well as structures built of metal containers [8]. NFPA 1403 also specifically defines an acquired structure as a building or structure acquired by the authority having jurisdiction from a property owner for the purpose of conducting live-fire training evolutions. Throughout the fire service, live-fire training structures have been considered to be concrete burn buildings (concrete, masonry, steel) as well as shipping containers or "conex" boxes which are typically either permanently installed on the grounds of a fire training academy or transported as mobile units via a truck and trailer. Acquired structures are commonly donated buildings, which were formerly occupied and now vacant, that have been designated for training. Construction of these structures can include Type III or Type V with wood-framed interior members. Finishes of acquired structures can include plaster and lath or drywall as used here. Because this structure was composed of interior wood framing with a drywall finish to include combustible structural elements such as the walls, floor, and roof assemblies, it was deemed an acquired structure for the purpose of this study.

The structure utilized for this set of experiments included a first floor that was of a similar layout to the single story structures utilized in the previous research studies on ventilation, all of which were conducted within the large scale fire laboratory on the grounds of Underwriters Laboratories in Northbrook, Illinois. Using a similar floor plan as previous DHS projects allowed for this test series, looking at wood-based training fuels in acquired structures, to be compared to the previous experiments with modern furnishings. The first floor was elevated one complete story above grade and incorporated a basement with interior staircase that led from the basement upstairs into the kitchen of the home. For the purpose of this study on acquired structures, the stairway to the basement was sealed closed, isolating the first floor. The first floor of the home served as the stand-alone test structure for these experiments. As such, the description of the structure is primarily focused on the first floor. The first floor of the structure as seen from the front is shown in Figure 3.1. The elevation of the first floor is seen in Figure 3.2.

Figure 3.1: Exterior view of the front of the structure on the level of the first floor.

Figure 3.2: Exterior view of the structure showing the first floor elevated atop the basement.

The outer wall of the basement was composed of interlocking concrete blocks 2.0 ft (0.6 m) wide, 2.0 ft (0.6 m) high, and 4.0 ft (1.2 m) long. The interior dimensions of the basement were 43.6 ft (13.3 m) wide, 23.9 ft (7.28 m) long, and 9.0 ft (2.74 m) high. The joints and gaps between the blocks were filled with high-temperature insulation. The walls were constructed from nominally 2.0 in. x 4.0 in. (3.8 cm by 8.9 cm) studs. The studs were lined with 0.5 in. (1.27 cm) cement board and 0.625 in. (1.59 cm) gypsum board. The floor assembly between the basement and first floor had engineered lumber I-joists along with two layers of 0.625 in. (1.59 cm) gypsum board. The exterior walls of the first floor were protected by 0.3 in. (8 mm.) thick fiber cement board siding, a layer of olefin home wrap, and 0.5 in. (1.3 cm.) oriented strand board (OSB). The walls were constructed from nominally 2.0 in. x 4.0 in. (3.8 cm. by 8.9 cm.) studs. The studs were lined with 0.5 in. (1.3 cm.) cement board and 0.5 in. (1.3 cm.) gypsum board. The interior dimensions of the first floor measured 45.2 ft (13.7 m) by 25.2 ft (7.7 m) with a 8.0 ft (2.4 m) ceiling (cf. Figure 3.3). Table 3.1 defines the size of the vents (area and sill) in Figure 3.3.

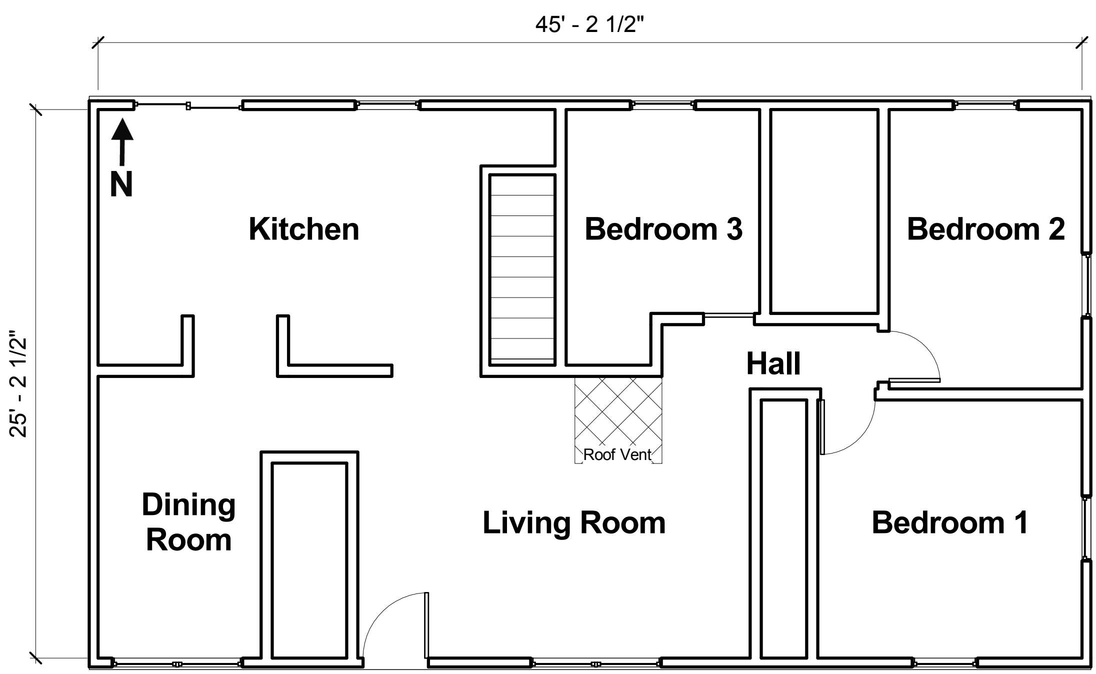


Figure 3.3: Plan view of the test structure with major dimensions and locations of vents. The dimensions (area and sill height) appear in Table 3.1.

Table 3.1: Test Structure Vent Legend

Icon	Vent	Dimensions
(slider icon)	Slider	72 in. W x 80 in. H
(single window icon)	Single Window	36 in. W x 60 in. H; 24 in. sill
(double window icon)	Double Window	72 in. W x 60 in. H; 24 in. sill

The only ventilation openings utilized on the first floor included the front door, Living Room window, Bedroom 1 windows, Bedroom 2 windows, and the roof vent. The remainder of the ventilation openings within the structure were covered from the interior with 0.5 in. (1.27 cm) cement board and secured as to not influence the fire dynamics via an inadvertent breakage of a remote window or failure of an interior door. The front door was of common size for a residential dwelling, 32 in. (81.2 cm.) by 80 in. (203.2 cm.), and was comprised of metal sheeting with a wood and polystyrene filled core. The remaining windows in the Living Room, Bedroom 1, and Bedroom 2 were framed openings within the wall and finished with drywall and drywall compound. A wood framed "shutter" finished with an outside layer of 0.5 in. (1.3 cm) plywood and inside layer of 0.5 in. (1.3 cm) cement board was affixed to the exterior of the framed window openings. These shutters served as windows for the repeated evolutions within the building and allowed for the window to be opened and closed as many times as needed during a given test. The ability for the shutter to open fully at a designated time was also a benefit to this design. Functionality like this is not possible with a standard glass window insert. Window shutters like this are common in other types of training buildings such as concrete burn buildings and metal shipping containers. The window shutters can be seen in Figure 3.4. These shutters were similar to those used in the previous fireground studies looking at horizontal ventilation, vertical ventilation, and positive pressure attack.

Figure 3.4: Exterior view of the window shutters.

The roof vent was located within the Living Room of the structure and was a 4.0 ft (1.2 m) by 4.0 ft (1.2 m) framed opening stretching from the ceiling surface through the attic space to finish above the incline of the roof decking. The roof vent was finished with two layers of 0.5 in. (1.27 cm) cement board and drywall compound to limit leakage. Atop the roof vent was a 4.5 ft (1.4 m) by 4.5 ft (1.4 m) wood framed hatch finished with 0.5 in. (1.3 cm) cement board. Steel cable was attached to the hatch and run through a wood-framed, high point change of direction and down to the ground level so the vent could be opened and closed from a safe location. A high point change of direction provides mechanical advantage to the firefighter and allows for ease of operating the vent. The interior and exterior structure of the roof vent can be seen in Figure 3.5.

Figure 3.5: View of the roof vent from the exterior (L) and interior (R). The interior view is from the Living Room looking up into the vent shaft. Note the bi-directional probe array located halfway between the hatch and the Living Room ceiling.

Eight of the 12 tests utilizing training fuels within acquired structures involved fires originating in the Living Room of the structure. The Living Room was 12.9 ft by 18.1 ft (3.9 m by 5.5 m) with 8.0 ft (2.4 m) ceiling height throughout. The Living Room had two exterior openings: the front door which was 32 in. by 80 in. (0.8 m by 2.1 m) and the Living Room window which was 72 in. by 60 in. (1.8 m by 1.5 m). There were three other framed openings into and out of the Living Room. There was an opening into the Kitchen which was 4.1 ft (1.2 m) wide, an opening into the Dining Room which was 3.5 ft (1.1 m) wide, and an opening to the Hallway which was 4.1 ft (1.2 m) wide. All openings were of full ceiling height at 8.0 ft (2.4 m). These areas remained open to one another at all times during the experiments. The remaining four of the 12 tests utilizing training fuels within acquired structures involved fires originating in the bedrooms of the home, specifically two tests in Bedroom 1 and two tests in Bedroom 2. Bedroom 1 in the structure was 12.1 ft by 11.8 ft (3.7 m by 3.6 m) and Bedroom 2 was 12.8 ft by 8.8 ft (3.9 m by 2.7 m). Both bedrooms had a uniform ceiling height of 8.0 ft (2.4 m). Each of these rooms had two exterior windows, measuring 36 in. by 60 in (0.9 m by 1.5 m). Additionally, each bedroom contained one doorway that led to the Hallway of the house and measured 30 in. by 80 in (81.2 cm by 203.2 cm). The doors to the bedrooms were removed and remained open during the experiments.

To characterize static ventilation within the structure, an air leakage measurement system was used to measure the amount of leakage associated with the structure before each test. The measurement is reported in air changes per hour at 50 Pa (ACPH50) and was obtained by using a fan to pressurize the structure. The unit ACPH50 represents the number of times the total volume of air in the structure changes in one hour as a result of pressurizing the interior to 50 Pa with the fan. The average leakage across all 12 experiments was 27.6 $\pm$ 2.2 ACPH50.

Fully dimensioned drawings of the first floor, including the location of all walls and vents, are included in Appendix B.

3.2 Instrumentation

The structure was instrumented for gas temperature, gas velocity, and gas concentration measurements. Gas temperatures were measured with both 0.05 in. (1.3 mm) bare-bead, Chromel-Alumel (Type K) thermocouples and 0.0625 in. (1.6 mm.) Inconel sheathed thermocouples. Sheathed thermocouples were also used in conjunction with the bi-directional probes for gas velocity measurements. Sheathed thermocouples allow the instrumentation to be placed in areas where suppression may occur to minimize the affect the water may have on the measurement. Bi-directional probes utilize differential pressure measurements to effectively determine the difference in high and low pressure for a given area. When coupled with the thermocouples as a temperature measurement, gas velocity can be determined. Gas concentrations included the measurement of oxygen, carbon dioxide, and carbon monoxide.

3.2.1 Instrumentation Details and Locations

Four bare-bead thermocouple arrays were installed on the first floor of the test structure. Each thermocouple array had eight individual thermocouples. The first was 1.0 in. (2.5 cm.) below the ceiling, and the remaining seven thermocouples were spaced in 1.0 ft (0.3 m) intervals below the ceiling (e.g. the bottom thermocouple was 7.0 ft (2.13 m) below the ceiling). Each thermocouple tree was centered within its respective room, as shown in Figure 3.6. Four stainless-steel taps for gas concentration measurements were installed; one centered along the west wall in Bedroom 2, one along the west wall of Bedroom 1 (1.0 ft (0.3 m) from the South wall), one centered along the south wall of the Hallway, and one along the east wall of the Living Room (1.0 ft (0.3 m) from the South wall). In all cases, the probes were 1.0 ft (0.3 m) above the floor.

Four bi-directional probe and Inconel-shielded thermocouple arrays were installed in the structure. One array was installed in the front door with the probes and thermocouples centered horizontally and equally spaced vertically in the opening. There were a total of five measurement points in this array labeled Top, Top Middle, Middle, Bottom Middle, and Bottom beginning with the probe closest to the top of the door frame. There were two other arrays with five measurement locations located on the first floor; one in the Living Room window, and one in the rear window to Bedroom 2. These arrays were also centered horizontally and equally spaced vertically within the opening, consisting of the same naming convention. The last array only contained three measurement locations and was positioned within the framed opening to the roof vent. The array was once again centered horizontally and vertically within the opening. Table 3.2 shows the icons used in the instrumentation floor plan in Section 3.2.1.

The measurement devices and respective locations within the structure were chosen based on the ability to compare the data acquired during these experiments to that of the previous experiments in the horizontal ventilation, vertical ventilation, and positive pressure attack studies [1–3].

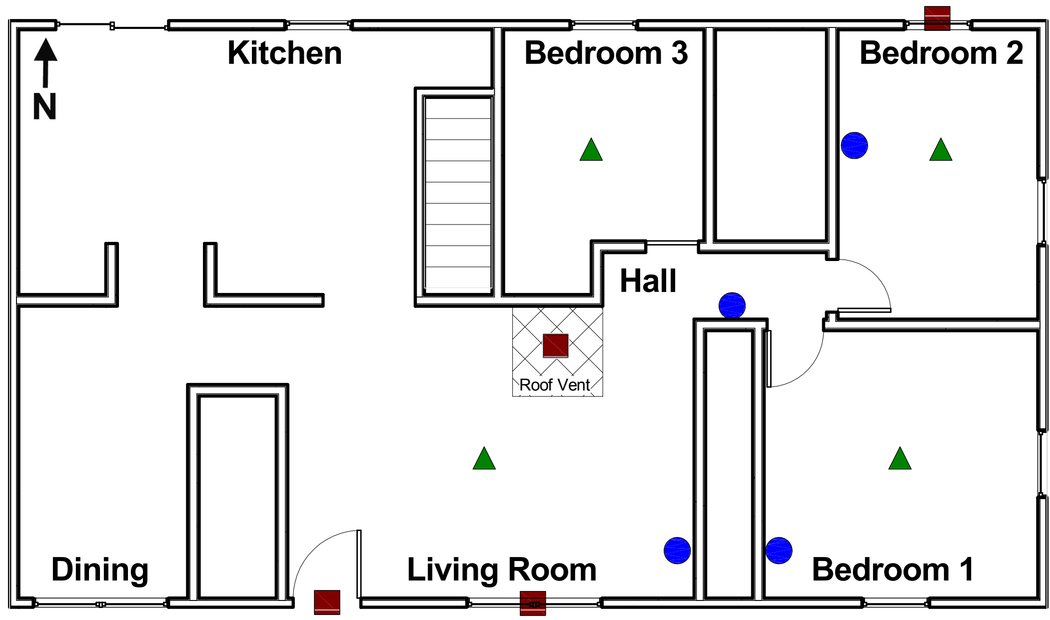
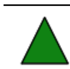


Figure 3.6: Instrumentation locations in the test structure. Table 3.2 describes each instrumentation icon.

Table 3.2: Instrumentation Legend

Icon	Instrumentation
	Thermocouple Array
	Bi-Directional Probe & Thermocouple Array
	Gas Concentration Tap (O_2, CO_2, CO)

3.2.2 Measurement Uncertainty

There are different components of uncertainty in the measured values reported in this document, specifically gas temperature, gas velocity, gas concentration, length, mass, and structure leakage. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those evaluated by statistical methods, and Type B are those evaluated by other means [19]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (− a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties can be combined in quadrature to yield the combined standard uncertainty. Multiplying this combined standard uncertainty by a coverage factor of two results in an expanded uncertainty with a 95 % confidence interval (2σ). For some components, such as the zero and calibration elements, uncertainties were derived from referenced instrument specifications. For other components, referenced research results and past experience with the instruments provided input for the uncertainty determination.

Gas Temperature According to Omega Engineering, the manufacturer of the thermocouple wire utilized during the experiments, the standard uncertainty in the temperature of the thermocouple wire itself is ± 2.2 °C at 277 °C and ± 9.5 °C at 871 °C [20]. In addition to the uncertainty of the sensor itself, radiative effects to the thermocouple should be considered. Several studies have attempted to quantify these effects on thermocouple measurement uncertainty in compartment fires [21,22]. These studies indicated that when the thermocouple is located in the upper gas layer, the actual temperature of the surrounding gas is typically higher than the measured temperature, 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 during a fully involved compartment fire, the percent error in measured temperature can be much larger. Because of these radiative contributions, the expanded total uncertainty is estimated as ± 15 %.

Gas Velocity A gas velocity measurement study that focused on flow through doorways during pre-flashover compartment fires yielded total expanded uncertainties ranging from ± 14 % to ± 22 % for measurements from bi-directional probes similar to those used throughout the experiments described in this report [23]. The total expanded uncertainty for gas velocity measured during these experiments is estimated to be ± 18 %.

Gas Concentration The oxygen concentration measurement range of the OxyMat6 was 0–25 %. The gas sampling instruments used throughout the experiments described in this report have demonstrated a relative expanded uncertainty of ± 1 % when compared to span gas volume fractions [24]. According to a study by Lock et al. [25], the non-uniformities and movement of exhaust gases in addition to the limited amount of sampling points considered in each experiment result in an estimated expanded uncertainty of ± 12 %.

Length Length measurements, such as the room dimensions and instrumentation locations, were made with either a hand held laser measurement device having an accuracy of 0.25 in. (± 6.0 mm) over a range of 2 ft (0.6 m) to 50 ft (15.2 m) [26] or ± 0.02 in. (± 0.51 mm) resolution steel measuring tapes manufactured in compliance with NIST Manual 44 [27], which specifies a tolerance of ± 0.06 in. (± 1.5 mm) for 30 ft (9.1 m) tapes and ± 0.25 in. (± 6.4 mm) for 100 ft (30.5 m) tapes. These uncertainties are all well within the precision of the reported dimensions, which are typically rounded to the nearest inch. Some issues, such as levelness of the device and "soft" edges on upholstered furniture, result in an estimated expanded uncertainty of ± 1.0 % for reported length measurements.

Mass The load cell used to weigh the fuels prior to the experiments had a range of 0 lb (0 kg) to 441 lb (200 kg) with a resolution of 0.11 lb (0.05 kg) and a calibration uncertainty within 1 % [28]. The total expanded uncertainty for the fuel weights measured by the load cell that are presented in this report is estimated to be less than ± 5 %.

Structure Leakage To characterize ventilation within the structure, an air leakage measurement system (Model 5101) was used to measure the amount of leakage associated with the training prop before each test [29]. *ASTM E779-10, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization* was followed to determine the air leakage rate of the prop before each experiment [30]. The measured leakage rates were recorded in units of air changes per hour at 50 Pa (ACPH50). Retrotec, the manufacturer of the leakage measurement system, reports an accuracy of ± 5 % for the system.

3.3 Fuel Loads

Two wood-based training fuel packages referred to as 1) pallets and 2) pallets and OSB were utilized in this study on acquired structures. These fuels have been characterized for heat release rate and burn characteristics with various weights and configurations in the report titled *Evaluation of the Thermal Conditions and Smoke Obscuration of Live Fire Training Fuel Packages* [9]. The fuel packages utilized have been consistent throughout the various parts of the study including: *Safety and Fidelity in Concrete Live Fire Training Buildings* as well as the *Evaluation of Ventilation-Controlled Fires in L-Shaped Training Props* [31, 32].

Fire department training academies typically use variations of pallet and straw fuel loads and incorporate a steel platform, otherwise known as a burn rack, for support and elevation within the compartment. Elevating the fuel package within the compartment allows oxygen to make it to the base of the fire, aiding in sustained combustion and consistent growth. Additionally, elevating the fuel within the space allows the flame to spread upwards and deflect off of the ceiling surface quicker, providing an effect of "rollover." A 4.0 ft (1.2 m) by 4.0 ft (1.2 m) platform located 1.0 ft (0.3 m) above the floor was used to support both of the fuel loads within these experiments. This was constructed of 2.0 in. (5.1 cm) by 2.0 in. (5.1 cm) tubular steel framing with an extruded steel mesh top. The location of the platform within the Living Room, Bedroom 1, and Bedroom 2 of the structure can be seen in Figure 3.7. Within Bedroom 2, the North side of the burn rack is located 15.0 in. (38.1 cm) off of the wall. In Bedroom 1, the East side of the burn rack is located 32.0 in. (81.3 cm) off of the wall. In the Living Room, the South side of the burn rack is located 50.0 in. (127.0 cm) off of the wall. The positioning of the burn rack remained the same regardless of the fuel package utilized.

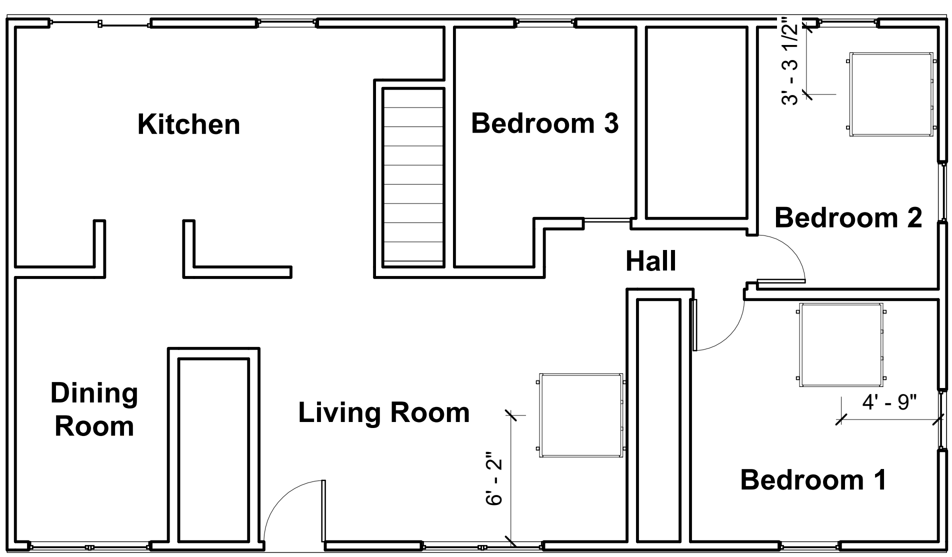


Figure 3.7: Locations of the burn rack within the test structure.

3.3.1 Pallets

A pallets fuel package is the most commonly utilized method of fuel loading for live-fire training as it incorporates materials that are both economically feasible and readily available. This fuel package abides by the live-fire training standard, NFPA 1403, and produces conditions that are predictable and repeatable. Fire departments throughout the world utilize pallets and straw in various configurations and quantities. For the purpose of these experiments, the pallets fuel package consisted of three pallets positioned in the shape of a triangle, in which one pallet was laid flat and the remaining two pallets were stood on end, leaning into one another. A bale of straw was scattered in the open spaces between the pallet slats, as well as the open cavity between the two standing pallets. The pallets fuel package can be seen in Figure 3.8. The average weight of each pallet was 38.5 lbs ± 5.8 lbs (17.4 kg ± 2.6 kg) and the average weight of each bale of straw was 30.8 lbs ± 4.3 lbs (13.9 kg ± 1.9 kg). The average weight of the fuel package in total for the six pallets experiments was 153.0 lbs ± 8.5 lbs (69.4 kg ± 3.8 kg). The pallets were supported via the steel burn rack discussed above. Remote ignition of this fuel package occurred within the straw via an electronic match in the center of the triangle.

Figure 3.8: Pallets fuel package.

3.3.2 Pallets & OSB

The limitations that the pallets fuel package has with regards to fire behavior during live-fire training is known by many instructors. The incorporation of OSB to the fuel package is often due to the idea that this fuel package will create a more "realistic" experience for the student. A common misconception is that change in fire behavior with OSB is from the different composition and resins within the material when it is likely due to the additional fuel mass and orientation which leads to efficient growth [9]. The pallets and OSB fuel package is similar to the pallets fuel package with the exception of adding three sheets of oriented strand board to the wall and ceiling surrounding the steel platform. The OSB is 7/16 in. (1.1 cm) in thickness and had an overall width and length of 4.0 ft (1.22 m) by 8.0 ft (2.44 m). Two full sheets were centered along the backside of the steel platform, stood vertically, and affixed to the wall of the structure by screws. The third sheet was centered over the steel platform and secured to the ceiling of the structure. The pallets and OSB fuel package can be seen in Figure 3.9. The average weight of a single sheet of OSB was 47.1 lbs $\pm$ 1.1 lbs (21.3 kg $\pm$ 0.5 kg). As mentioned in Section 3.3.1, the average weight of each pallet was 38.5 lbs $\pm$ 5.8 lbs (17.4 kg $\pm$ 2.6 kg) and the average weight of each bale of straw was 30.8 lbs $\pm$ 4.3 lbs (13.9 kg $\pm$ 1.9 kg). This brings the average total fuel package weight (three pallets, three sheets of OSB, and one bale of straw) to a total of 296.7 lbs $\pm$ 8.3 lbs (134.6 kg $\pm$ 3.8 kg). Similar to the pallets fuel package, these pallets are also located atop the steel burn rack. The location of the platform within the Living Room, Bedroom 1, and Bedroom 2 can be seen in Figure 3.7. Remote ignition of this fuel package also occurred within the straw via an electronic match in the center of the triangle.

Figure 3.9: Pallets & OSB fuel package.

3.3.3 Furniture

Experiments conducted in the previous research projects that examined horizontal ventilation, vertical ventilation, and positive pressure attack used furniture composed of synthetic materials and foam plastics as a fuel load. These experiments are used for comparison within this report. The orientation of these furnishings can be seen in Figure 3.10. Furniture dimensions and weights can be found in Appendix A for each respective project. The furnishings of interest for this comparison include those in the Living Room, Bedroom 1, and Bedroom 2 in the structure. These were the only rooms furnished with wood-based fuel packages during this study.

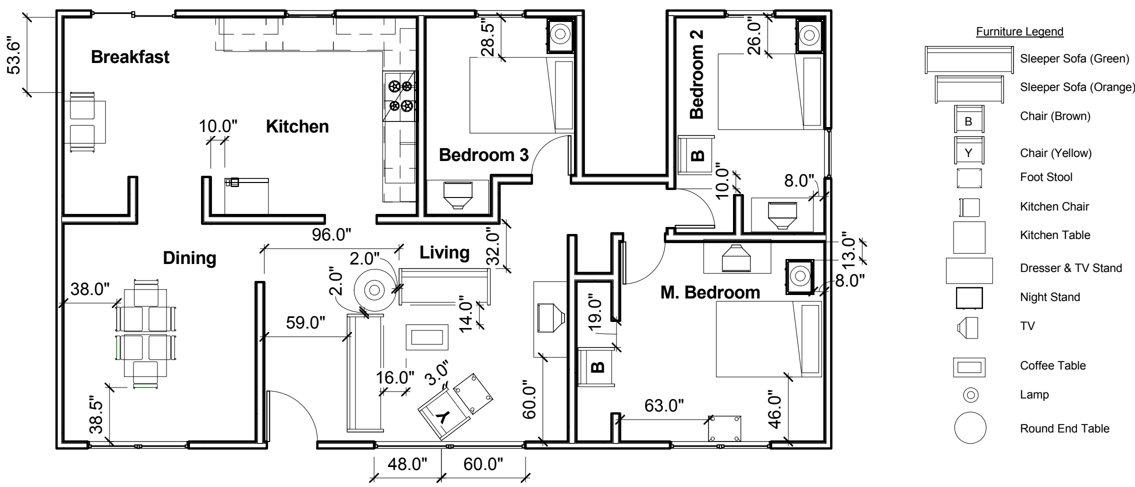


Figure 3.10: Furniture orientation and dimensions within the test structure.

The Living Room was furnished with two sleeper sofas, a television, television stand, ottoman, round end table, coffee table, chair, two pictures, lamp with shade, and two curtains. The floor was covered with polyurethane foam padding and polyester carpeting above a wooden sub-floor. The master bedroom (Bedroom 1) and rear bedroom (Bedroom 2) were furnished with a queen bed comprised of a mattress, box spring, wood frame, two pillows, a flat sheet, and comforter. The remainder of the room included a dresser, television, nightstand, lamp with shade, and an upholstered chair. The floor was covered with polyurethane foam padding and polyester carpeting above a wooden sub-floor. Figure 3.11 shows the Living Room and Bedroom furniture setup within the structure utilized during the positive pressure experiments [3].

Figure 3.11: Furniture Fuel Loading: Living Room & Bedroom

3.3.4 Fuel Mass and Orientation Discussion

The three fuel packages analyzed within this report were of different overall weights. This includes the two wood-based fuel packages tested in acquired structures for this portion of the training fires study as well as the furniture fuel loads from the previous fireground research. The pallets fuel package was on average 153.1 lbs ± 8.5 lbs (69.4 kg ± 3.8 kg). The pallets and OSB fuel package was on average 296.7 lbs ± 8.3 lbs (134.5 kg ± 3.7 kg). The pallets and OSB fuel package was an additional 143.7 lbs (65.2 kg) on average which was close to double the overall mass. The living room furnishings in the PPA study added up to a total of 568.8 lbs (257.5 kg) while the bedroom furnishings added up to a total of 406.2 lbs (184.2 kg). The weights of the furnishings did not include the polyester carpeting, polyurethane foam padding, or the wooden sub-floor which were also contributing items to the fuel load. As such, the overall mass of the fuel loads increased from the pallets fuel package to the pallets and OSB fuel package to the furniture fuel packages.

The report titled *Evaluation of the Thermal Conditions and Smoke Obscuration of Live Fire Training Fuel Packages* [9] highlights the importance of fuel mass and orientation to the overall fire size in addition to discussing the composition of the fuel. Figure 3.12 shows a comparison of four different *NFPA 1403* compliant wood-based fuel package setups characterized as a part of the study. The top left of the figure shows the pallets fuel package referenced throughout this report. The top right shows the free burn version of the pallets and OSB fuel package. It should be noted that the third sheet located above the pallets is not included here because these were free burns and were not in a compartment with a ceiling. The bottom left shows the horizontal configuration of the pallets fuel load and the bottom right shows additional pallets added and stacked vertically. These were burned in the open, without any compartmentation effects, underneath a calorimetry hood inside the laboratory facility at Underwriters Laboratories LLC headquarters in Northbrook, IL.

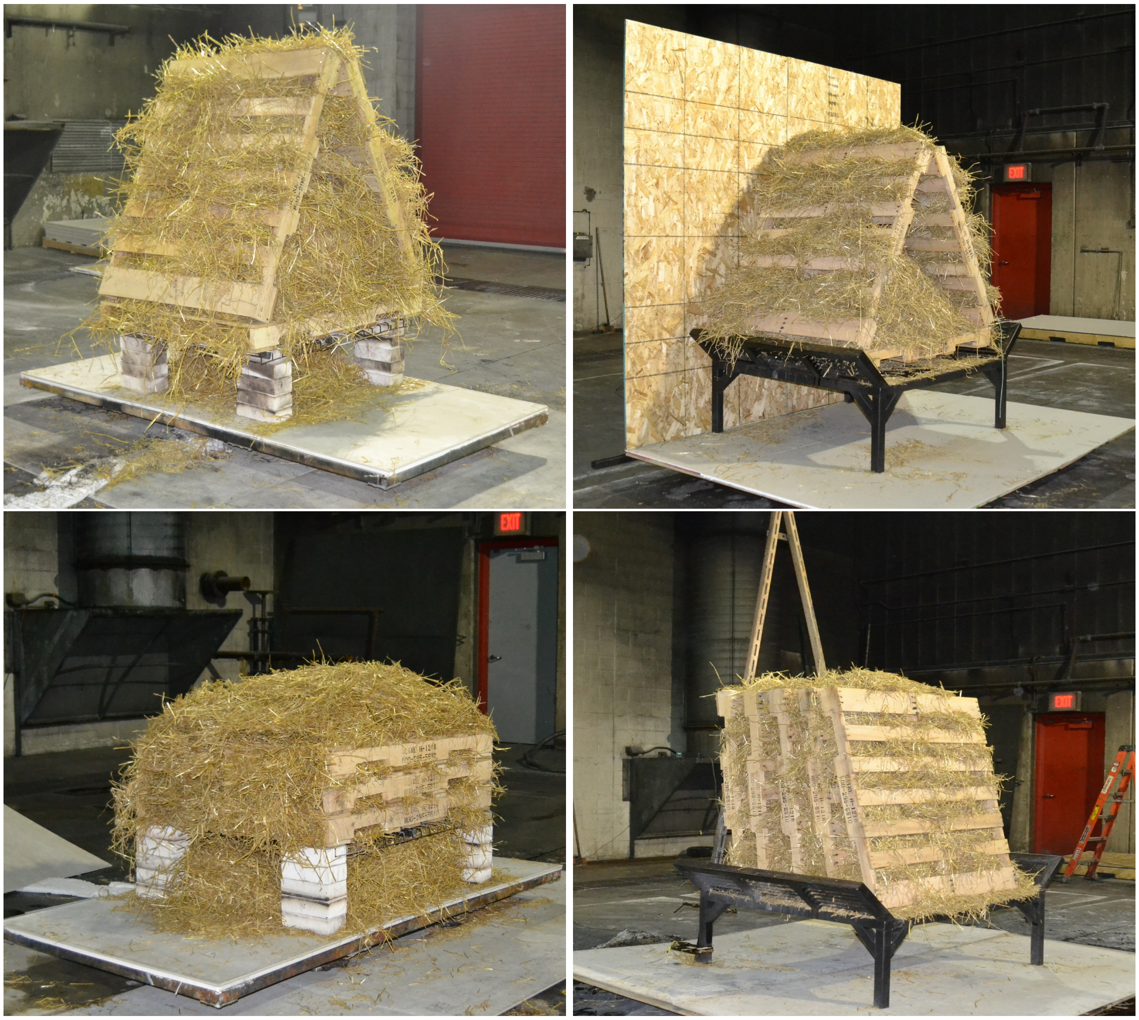


Figure 3.12: Wood-based fuel packages used in the heat release rate comparison from the *Training Fuels* report. [9]

Figure 3.13 shows the heat release rates of these four *NFPA 1403* compliant wood-based fuel packages. The three pallets and one bale of straw in a triangle, shown by the green line, is the base pallets configuration tested in acquired structures. The three pallets and one bale of straw with two vertical sheets of OSB, shown by the blue line, is a close variation to the pallets and OSB configuration tested in acquired structures. As mentioned above, it should be noted that the third sheet of OSB which is typically mounted or hung from the ceiling above the pallets is not included here as these were free burns, without a compartment ceiling. The three pallets and one bale of straw stacked horizontally, shown by the red line, uses the same amount of fuel as the traditional pallets configuration, just in a different orientation. The five pallets and one bale of straw shown by the orange line is another variant of the traditional pallets configuration which is intended to simulate additional mass in a similar orientation.

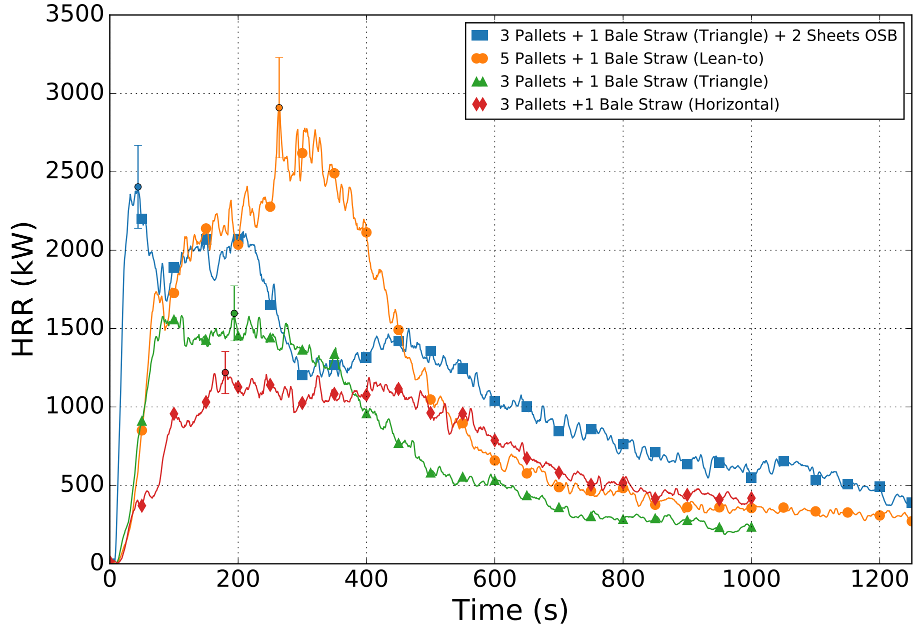


Figure 3.13: Heat release rate data from the *Training Fuels* report [9] showing a comparison between four wood-based fuel packages of varying mass and orientation.

The base configuration of the pallets fuel load shows rapid growth due to the surface to mass ratio of the straw dispersed throughout the setup and reaches a peak of 1.5 MW followed by a period of steady burning before a slow decay. The pallets and OSB shows the quickest growth to its highest peak of close to 2.5 MW followed by a slow decay. The quickest growth is due to the vertical orientation of the OSB which allows for rapid spread. The addition of OSB to the base pallets fuel package increased the HRR by nearly 1.0 MW. This could lead to the belief that the composition of the OSB is what drove the increased HRR. However, the five pallets and straw fuel package rose to a peak of close to 3.0 MW. While the initial growth was a bit slower and more comparable to the standard pallets configuration, the additional mass present here allowed the fuel package to have a HRR of approximately 0.5 MW higher than the OSB case. This shows that the fuel mass is of greater importance than the composition of the wood-based material when looking at the peak HRR. The effective heat of combustion of these fuel package materials confirms this as discussed in the *Training Fuels* report [9]. In order to examine the orientation changes of the fuel package, a sample was tested where a similar mass to the base pallets and straw configuration was oriented horizontally instead of the triangle used in acquired structures. The HRR data shows that the three pallets and one bale of straw stacked horizontally experiences slower growth due to the orientation and inability for quick consumption of the straw which is more compacted in this configuration. The peak of the HRR is slightly over 1.0 MW. Comparing the horizontal package to the triangle package, which are both of similar mass, show the differences between the growth rate and peak HRR are attributable to the orientation of the fuel package as hypothesized.

Separately, one of the container experiments conducted looked at adding pallets to the base fuel package in place of the OSB, but placed in the same location. See Figure 3.14 for this configuration. This resulted in a similar magnitude of peak thermal conditions within the test prop including heat flux and hot gas layer temperatures. This experiment also highlights that the fuel mass and configuration are of more significance than the composition of wood-based fuel. If the fuel masses are similar, and the fuel is oriented in the same manner, the behavior and resulting thermal conditions in the test prop are similar [9] when using NFPA 1403 compliant wood-based fuels. These conclusions hold true for both the free burn tests conducted in the laboratory and the compartment experiments conducted in training containers.

Figure 3.14: Fuel package configuration comparing pallets to OSB in the *Training Fuel Packages* study. [9]

In these acquired structure experiments, the pallets and OSB setup was almost twice the mass of the base fuel package of only pallets. Additionally, the mass of both wood-based fuel packages was an order of magnitude less than the furnishings utilized in the fireground ventilation research conducted previously [1–3]. This needs to be highlighted with regards to any differences noted in the tactical consideration comparison discussion to follow. Additional fuel mass and different orientations and configurations (amount of exposed surface area and height within the space) of the wood-based fuel packages are likely factors for some of the differences.

4 Experimental Procedure

Twelve experiments were conducted in Spring 2018 at the Delaware County Emergency Services Training Center in Sharon Hill, PA as a part of the *Study of the Fire Service Training Environment* project. The experiments were designed to examine fire conditions produced by two types of fuel packages across six different ventilation profiles in an acquired structure. The ventilation profiles involved three types of fire service ventilation — horizontal, vertical, and positive pressure. Table 4.1 contains specific details of the experiments and the sections that follow describe the experimental procedure used for each ventilation configuration.

Table 4.1: Experiment Details

Exp #	Fire Location	Vent Type	Vent Profile	Vent Location	Fuel Load
1	Living Room	Horiz	Front Door + Living Room Window	Near	Pallets
2	Living Room	Horiz	Front Door + Living Room Window	Near	Pallets & OSB
3	Living Room	Horiz	Front Door + Bedroom 2 Rear Window	Far	Pallets
4	Living Room	Horiz	Front Door + Bedroom 2 Rear Window	Far	Pallets & OSB
5	Living Room	Vert	Front Door + Roof Vent	Near	Pallets
6	Living Room	Vert	Front Door + Roof Vent	Near	Pallets & OSB
7	Bedroom 1	Vert	Front Door + Roof Vent	Far	Pallets
8	Bedroom 1	Vert	Front Door + Roof Vent	Far	Pallets & OSB
9	Bedroom 2	PPA	Front Door + Bedroom 2 Windows	Near	Pallets
10	Bedroom 2	PPA	Front Door + Bedroom 2 Windows	Near	Pallets & OSB
11	Living Room	PPA	Front Door + Bedroom 2 Rear Window	Far	Pallets
12	Living Room	PPA	Front Door + Bedroom 2 Rear Window	Far	Pallets & OSB

4.1 Experiments 1 & 2: Horizontal Ventilation, Near Vent

Experiments 1 and 2 involved horizontal ventilation near to the seat of the fire testing both the pallets and pallets & OSB fuel loads, respectively. Ignition occurred in the Living Room via an electronic match in the center opening of the pallet stack. The fire grew uninhibited with all vents initially closed. The front door was ventilated eight minutes after ignition. Seventeen seconds later, the Living Room window was ventilated. Then, the fire was allowed to grow to a new steady state before suppression was initiated. Figure 4.1 summarizes the interventions performed during the two experiments.

Experiments 1 and 2 were designed to be compared to Horizontal Experiment 3 from the study *Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction* [1], which used furniture composed of synthetic materials and foam plastics as a fuel load. The experiment was designed to simulate a crew making entry through the front door shortly before horizontal ventilation occurred via a window opening near the seat of the fire.

Event	Experiment 1	Experiment 2
Ignition	00:00	00:00
Front Door Open	08:00	08:00
Living Room Window Open	08:17	08:17
Suppression	11:18	10:47

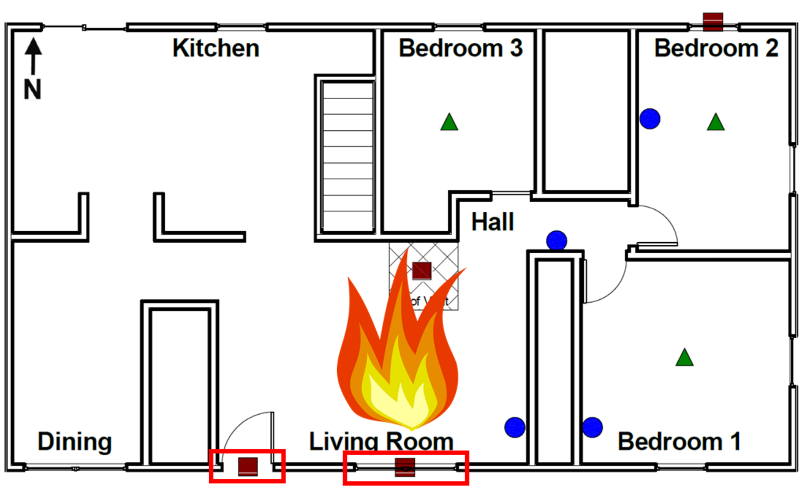


Figure 4.1: Floor plan showing ignition location (flame icon) and vents that were opened (red outlines) during Experiment 1 and Experiment 2. Event times for the experiments are provided in the table above the floor plan.

4.2 Experiments 3 & 4: Horizontal Ventilation, Far Vent

Experiments 3 and 4 involved horizontal ventilation far from the seat of the fire testing both the pallets and pallets & OSB fuel loads, respectively. Ignition occurred in the Living Room via an electronic match in the center opening of the pallet stack. The fire grew uninhibited with all vents initially closed. The front door was ventilated at eight minutes after ignition. Fifteen seconds later, the Bedroom 2 rear window was ventilated. Then, the fire was allowed to grow to a new steady state before suppression was initiated. Figure 4.2 summarizes the interventions performed during the two experiments.

Experiments 3 and 4 were designed to be compared to Horizontal Experiment 7 from the study *Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction* [1], which used furniture primarily composed of synthetic materials and foam plastics as a fuel load. The experiment was designed to simulate a crew making entry through the front door shortly before horizontal ventilation occurred via a window opening remote from the seat of the fire.

Event	Experiment 3	Experiment 4
Ignition	00:00	00:00
Front Door Open	08:00	08:00
Bedroom 2 Rear Window Open	08:15	08:15
Suppression	13:33	12:00

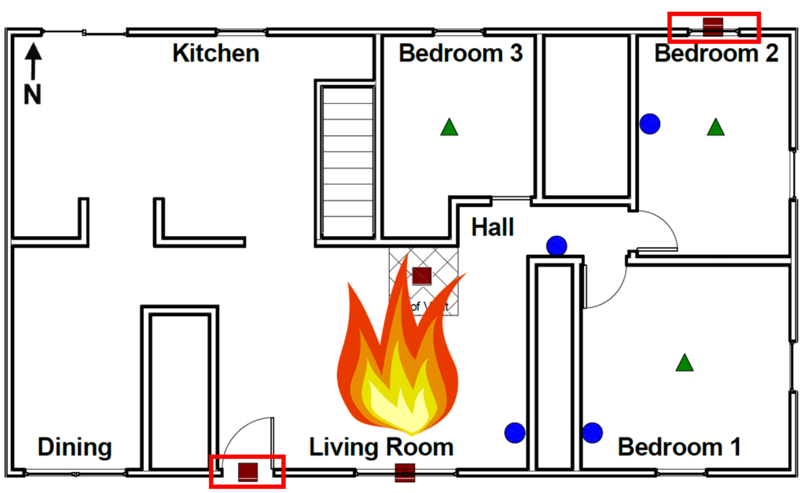


Figure 4.2: Floor plan showing ignition location (flame icon) and vents that were opened (red outlines) during Experiment 3 and Experiment 4. Event times for the experiments are provided in the table above the floor plan.

4.3 Experiments 5 & 6: Vertical Ventilation, Vent Above

Experiments 5 and 6 involved vertical ventilation near the seat of the fire testing both the pallets and pallets & OSB fuel loads, respectively. Ignition occurred in the Living Room via an electronic match in the center opening of the pallet stack. The fire grew uninhibited with all vents initially closed. The front door was ventilated at eight minutes after ignition. Approximately one minute and 45 seconds later, the roof vent was ventilated. Then, the fire was allowed to grow to a new steady state before suppression was initiated. Figure 4.3 summarizes the interventions performed during the two experiments.

Experiments 5 and 6 were designed to be compared to Vertical Experiment 5 from the project *Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes* [2], which used furniture primarily composed of synthetic materials and foam plastics as a fuel load. The experiment was designed to simulate firefighters ventilating the front door, chocking it completely open, and ventilating vertically directly above the seat of the fire.

Event	Experiment 5	Experiment 6
Ignition	00:00	00:00
Front Door Open	08:00	08:00
Roof Vent Open	09:47	09:46
Suppression	14:36	11:16

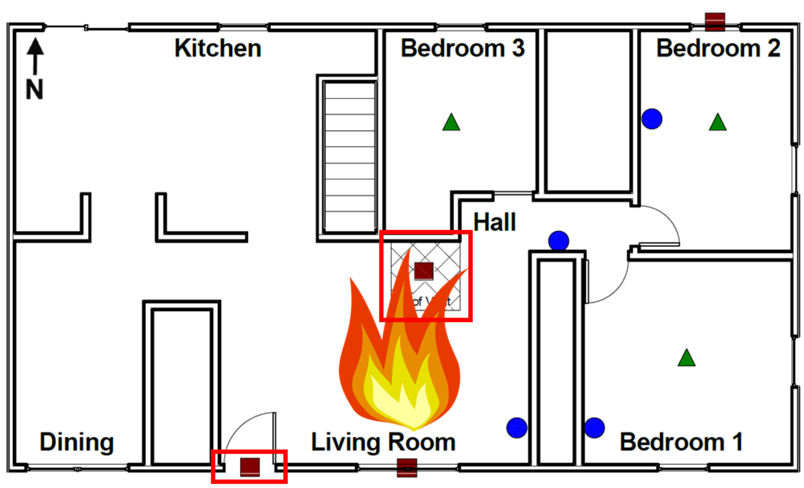


Figure 4.3: Floor plan showing ignition location (flame icon) and vents that were opened (red outlines) during Experiment 5 and Experiment 6. Event times for the experiments are provided in the table above the floor plan.

4.4 Experiments 7 & 8: Vertical Ventilation, Vent Remote

Experiments 7 and 8 involved vertical ventilation far from the seat of the fire testing both the pallets and pallets & OSB fuel loads, respectively. Ignition occurred in Bedroom 1 via an electronic match in the center opening of the pallet stack. The fire grew uninhibited with all vents initially closed. The front door was ventilated at eight minutes after ignition. Three minutes later, the roof vent was ventilated. Then, the fire was allowed to grow to a new steady state before the Bedroom 1 window was ventilated. One minute and 15 seconds later, suppression was initiated. Figure 4.4 summarizes the interventions performed during the two experiments.

Experiments 7 and 8 were designed to be compared to Vertical Experiment 9 from the project *Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes* [2], which used furniture primarily composed of synthetic materials and foam plastics as a fuel load. The experiment was designed to simulate a bedroom fire during which firefighters ventilated the front door, chocked it completely open, vented vertically above the living room (remote from the seat of the fire), and then vented the window of the bedroom.

Event	Experiment 7	Experiment 8
Ignition	00:00	00:00
Front Door Open	08:00	08:00
Roof Vent Open	11:00	11:00
BR1 Window Open	15:15	15:15
Suppression	16:30	16:30

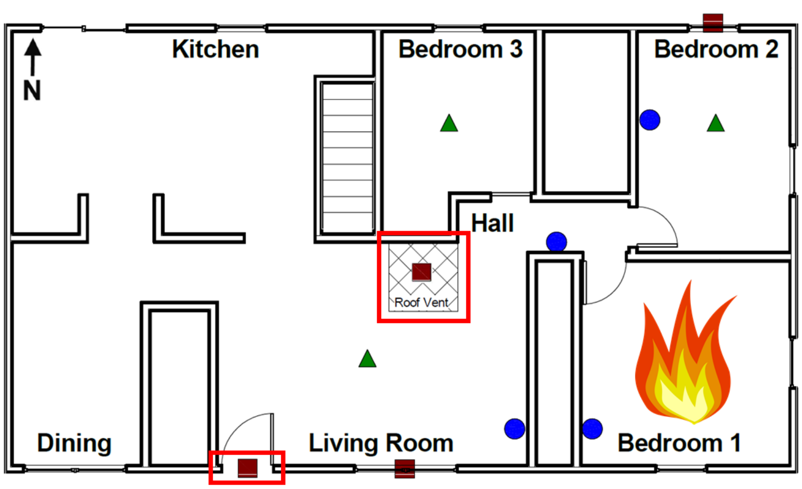


Figure 4.4: Floor plan showing ignition location (flame icon) and vents that were opened (red outlines) during Experiment 7 and Experiment 8. Event times for the experiments are provided in the table above the floor plan.

4.5 Experiments 9 & 10: Positive Pressure Attack, Near Vent

Experiments 9 and 10 involved positive pressure attack with the exhaust near the seat of the fire testing both the pallets and pallets & OSB fuel loads, respectively. Ignition occurred in Bedroom 2 via an electronic match in the center opening of the pallet stack. The fire grew uninhibited with all vents initially closed. The Bedroom 2 rear window was ventilated seven minutes after ignition. Thirty seconds later, the front door was opened. Then the fan, located outside the front door, was turned on 30 seconds later. One minute and 50 seconds later, the Bedroom 2 side window was opened and suppression followed about one minute later. Figure 4.5 summarizes the interventions performed during the two experiments.

Experiments 9 and 10 were designed to be compared to PPA Experiment 6 from the project *Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices* [3], which used furniture primarily composed of synthetic materials and foam plastics as a fuel load. The experiment was designed to simulate a fire in the Bedroom 2 to examine vent area on the effectiveness of positive pressure attack with the fan intake at the front door and the fan exhaust being the two Bedroom 2 windows.

Event	Experiment 9	Experiment 10
Ignition	00:00	00:00
BR2 Rear Window Open	07:00	07:00
Front Door Open	07:30	07:30
Fan On	08:00	08:00
BR2 Side Window Open	09:50	09:50
Suppression	11:50	11:40

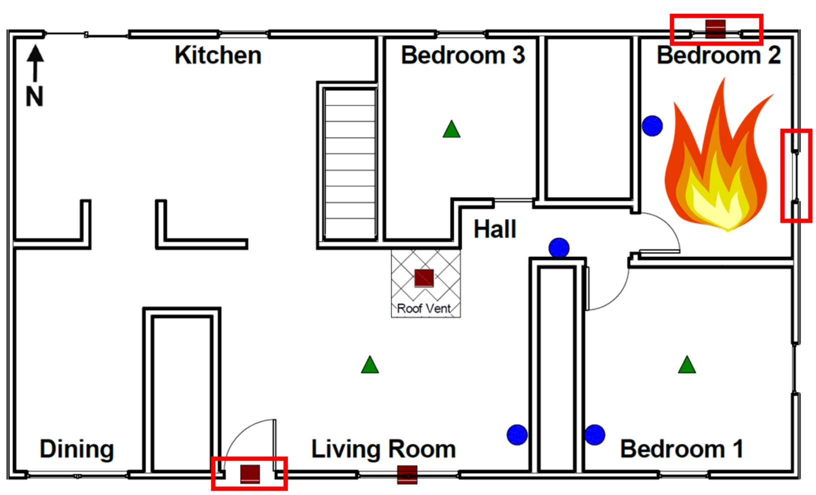


Figure 4.5: Floor plan showing ignition location (flame icon) and vents that were opened (red outlines) during Experiment 9 and Experiment 10. Event times for the experiments are provided in the table above the floor plan.

4.6 Experiments 11 & 12: Positive Pressure Attack, Far Vent

Experiments 11 and 12 involved positive pressure attack with the exhaust far from the seat of the fire testing both the pallets and pallets & OSB fuel loads, respectively. Ignition occurred in the Living Room via an electronic match in the center opening of the pallet stack. The fire grew uninhibited with all vents initially closed. The Bedroom 2 window was ventilated six minutes after ignition. Thirty seconds later, the front door was opened. Then the fan, located outside the front door, was turned on 30 seconds later and suppression was initiated about four minutes after the fan was turned on. Figure 4.6 summarizes the interventions performed during the two experiments.

Experiments 11 and 12 were designed to be compared to PPA Experiment 4 from the project *Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices* [3], which used furniture composed of synthetic materials and foam plastics as a fuel load. The experiment was designed to simulate a fire in the Living Room to examine the hazards of positive pressure attack with a remote exhaust ventilation opening with the fan intake as the front door and the fan exhaust as the rear Bedroom 2 rear window.

Event	Experiment 11	Experiment 12
Ignition	00:00	00:00
BR2 Rear Window Open	06:00	06:00
Front Door Open	06:30	06:30
Fan On	07:00	07:00
Suppression	11:05	11:00

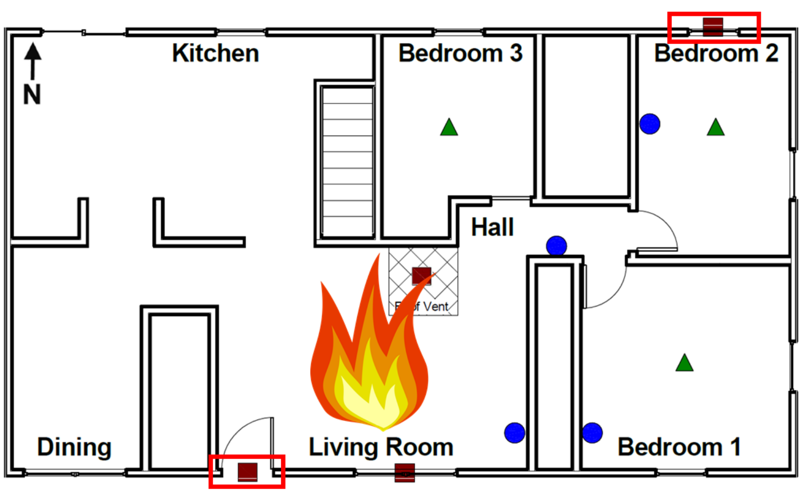


Figure 4.6: Floor plan showing ignition location (flame icon) and vents that were opened (red outlines) during Experiment 11 and Experiment 12. Event times for the experiments are provided in the table above the floor plan.

5 Fireground Tactical Consideration Comparison

Within the following sections, comparisons are made to tactical considerations developed as a part of the previous studies analyzing horizontal ventilation, vertical ventilation, and positive pressure attack [1–3]. The previous studies used furniture composed of synthetic materials and foam plastics as a fuel load within single family homes to provide recommendations to the fire service about how various means of ventilation affect fire dynamics and the implementation of fireground tactics. The experiments described in this report were conducted in a structure similar to that used during the previous studies and utilized NFPA 1403 compliant wood-based fuels. This allowed for a comparison between experiments with wood-based fuels and modern furnishings to determine if the tactical considerations developed for the fireground hold true on the training ground when conducting live-fire evolutions in acquired structures.

The three priorities of the fire service mission include life safety, incident stabilization, and property protection. Life safety includes not only the public who may be trapped within the structure but the responding firefighters as well. Ventilation and suppression interventions on the fireground have the ability to impact the life safety of everyone involved. The main purpose of ventilation is to aid firefighters in the task of suppression as well as remove toxic smoke and fire gases from the structure to increase victim survivability when coordinated appropriately. Unfortunately, when not used in coordination with suppression, ventilation of a ventilation controlled fire can decrease survivability in the structure and make conditions worse for both firefighters and trapped occupants alike [1–3].

The focus of this study on the fire service training environment looks at wood-based training fuels in acquired structures for the purpose of improving the understanding of the training ground and how it relates to the fireground. By instrumenting the structure for these experiments, temperature can be used as a measure of tenability. Because the study is focused on live-fire training evolutions and not the fireground, tenability limits discussed will be in reference to only firefighters occupying the space wearing full protective clothing and self contained breathing apparatus.

Firefighters operating within acquired structures during training evolutions can routinely be exposed to conditions that have the potential to cause injury or death. Understanding how the personal protective ensemble is intended to function is critical to avoid complications during training. As firefighters are exposed to elevated temperatures during training, their PPE absorbs energy due to elevated temperatures and heat flux. Depending on the time exposed and associated heat flux (both convective and radiative), the ensemble becomes saturated with heat and begins transferring energy to the firefighter. As such, standards are in place for the testing of various pieces of the PPE including NFPA 1971 which requires that protective clothing withstand exposure to 500 °F (260 °C) for five minutes without substantial damage [33]. For this discussion of tenability within acquired structures, the PPE testing threshold of 500 °F (260 °C) is considered to be the upper limit for a firefighter to remain in the environment for a short period of time. The temperatures referenced throughout the sections below were evaluated at 3.0 ft above the floor. This height is typically associated with the head height of firefighters crawling or kneeling.

It should be noted that a tenability analysis based on temperature alone does not paint the full picture. Heat flux measurements along with a firefighters time of exposure are required to provide a more detailed analysis of when conditions may become untenable. Depending on the location of the firefighter inside the structure, radiant energy from the wood-based training fuel load may cause saturation of the personal protective ensemble even though temperatures within the space may be relatively low. Additionally, the time a firefighter is exposed to elevated temperatures and increased thermal load, either through convective or radiative heat flux, dictates the point in which conditions are no longer considered tenable [34]. A firefighter operating on the interior of a structure during a training evolution in temperatures below PPE testing thresholds for a long period of time may cause the gear to become increasingly saturated with energy which will eventually transfer to the firefighter causing burn injury. With that being said, a tenability discussion based on the temperature reference for PPE testing provides the end user with an increased understanding into how different live-fire training evolutions can impact the exposure to both instructors as well as students. The temperature charts shown throughout the comparisons below have a red horizontal line at 500 °F (260 °C) to provide a visual representation of PPE testing limits with respect to discussion on firefighter tenability.

One of the main discussion points throughout the comparisons between fuel packages and ventilation types is the response to ventilation and subsequent start of regrowth in the fire room. The start time of fire regrowth relative to the first fire service intervention was determined for every experiment. The first fire service intervention was the front door open for the horizontal and vertical ventilation experiments and the Bedroom 2 rear window open for the positive pressure attack experiments. This parameter, referred to as "regrowth time," is defined as the time at which the temperature measured by the thermocouple 1.0 ft. (0.3 m) below the ceiling of the fire room started to increase in response to fire growth following the first fire service intervention. The thermocouple at 1.0 ft. (0.3 m) below the ceiling was chosen over the 1.0 in. (25 mm) thermocouple because this location was consistent across both these experiments in addition to the experiments used for comparison from the previous research studies [1–3]. A temperature increase was determined to be in response to fire regrowth if the temperature increased with each measurement over a span of five seconds (i.e. five measurement points because temperature data was collected at once every second) and if the temperature after the five second increase was measurably larger than the temperature at the start of the increase (greater than 15 % which is the estimated measurement uncertainty). The temperature charts shown throughout the comparisons below may have a black "star" icon, which is the visual representation of the point in time at which fire regrowth began as measured by the fire room thermocouple at 1.0 ft. (0.3 m) below the ceiling.

Suppression tactics were not analyzed as a part of this study. As such, tactical considerations from the previous projects that are not consistent with the scope and limitations of this study will not be compared within this report. Each comparison below will begin with a short description of the tactical consideration as found within the previous project reports.

5.1 Horizontal Ventilation

The tactical considerations produced by the previous project titled *Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction* [1] are listed below. The listed items shaded gray were deemed to be outside the scope of this study and therefore are not considered during the comparison of experimental results to the tactical considerations. As discussed in Section 1.2, the number of experiments allotted for horizontal ventilation limited the scope and amount of variables able to be tested. Horizontal ventilation was limited to the front door and a single window opening, and thus tactical considerations regarding additional flow paths and quantity of openings are not discussed. Additionally, there was not a closed door component to this test, nor was suppression a variable, and as such, these are not discussed as comparisons.

Experiments 1 — 4 with wood-based fuels in acquired structures examined horizontal ventilation. Experiments 3 and 7 from the fireground horizontal ventilation research conducted previously [1] are utilized as comparisons with similar vent profile and fire location.

Table 5.1: Horizontal Ventilation Study Tactical Considerations

Tactical Consideration Title	Section
Stages in Fire Development: Ventilation Limited Growth Curve	5.1.1
Forcing the Front Door is Ventilation	5.1.2
Nothing Showing Means Nothing	5.1.3
Coordination of Fire Attack	5.1.4
Smoke Tunneling and Rapid Air Movement in Through Front Door	5.1.5
VES - Importance of Isolation	5.1.6
Flow Paths - Every Vent Opening Changes the Flow Paths	N/A
Can You Vent Enough	N/A
Impact of a Closed Door	N/A
Potential of Pre-Existing Ventilation Openings	N/A
Pushing Fire	N/A
No Damage to Surrounding Rooms	N/A

5.1.1 Stages in Fire Development: Ventilation Limited Growth Curve

Fireground Tactical Consideration Summary: *The stages of fire development change when a fire becomes ventilation limited. It is common with today's fire environment to have a decay period prior to flashover which emphasizes the importance of ventilation [1].*

The fuel-limited fire curve shown in Figure 5.1 is referenced in firefighting training literature [35]; however, this type of growth rarely translates to conditions seen on the fireground. This type of fire growth can occur with a free burning object in the open or with a smaller fuel package inside a large compartment. When conducting live-fire evolutions in acquired structures, it should be noted that ventilation limited behavior can be achieved with NFPA 1403 compliant fuel packages.

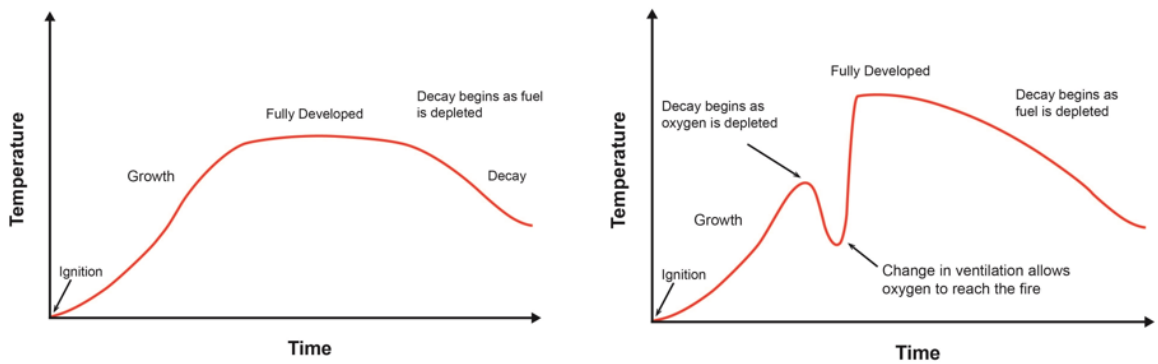


Figure 5.1: Time vs. Temperature (Left: Ideal Fuel Controlled Fire Growth Curve; Right: Idealized Ventilation Controlled Fire Growth Curve)

As with furniture fuel loads tested in the previous Horizontal Ventilation study, the wood-based training fuels tested within the acquired structure also show a ventilation-limited growth curve when following the same ventilation sequence (front door followed by window vent). Figure 5.2 shows the fire room growth curves associated with the horizontal near vent experiments. Near vent is reference to the experiments in which the horizontal ventilation opening is made in the fire room, near to the seat of the fire.

Pre-ventilation is defined as the period from ignition until the first fire department intervention, which was typically either the front door or bedroom window being opened. No exterior vents within the structure were open, and the ventilation profile was considered to be "all closed." After ignition, the temperatures began to increase continuously until an initial peak was reached. The rate of temperature rise within the fire room was dependent on the fuel package material and configuration. The wood-based fuels experienced quicker growth due to the high surface area to mass ratio present with the pallets and dispersed bale of straw. Due to the lack of a continued source of oxygen within the structure, the fires enter a decay period after the initial peak, where the temperatures began to decline in the fire room. As combustion decreased due to the lack of oxygen present, temperatures in the structure continued to decrease. This trend was present until the first fire department intervention, which provided a new source for oxygen. Both wood-based training fuels and furniture exhibited similar behavior where temperatures began to decline prior to the front door being opened. Once the front door was opened, followed closely by the front window, new sources of oxygen were present, and the fire reacts accordingly. Regrowth occurs in the compartment and the fires grow to a new steady state post ventilation.

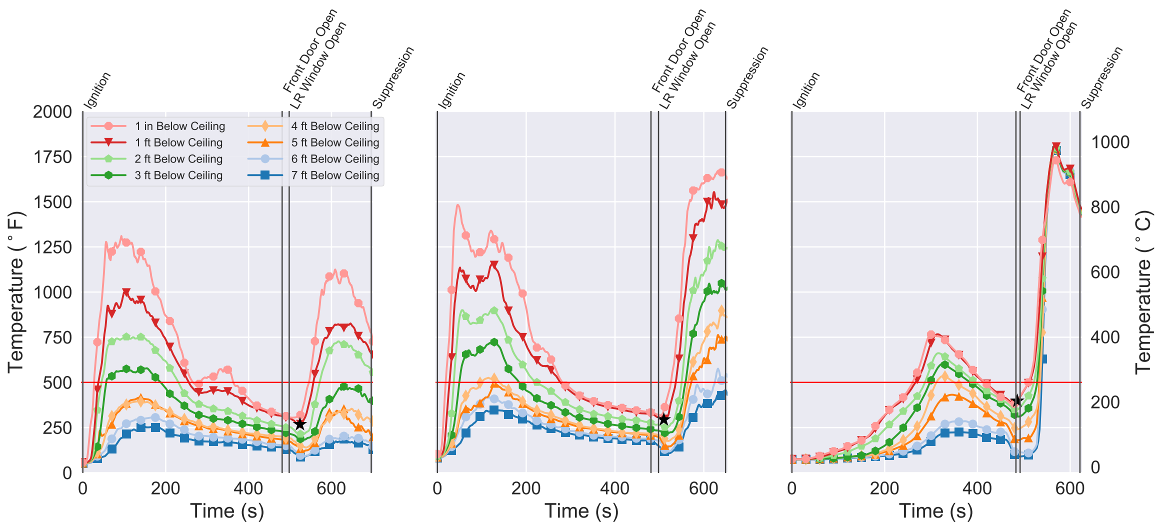


Figure 5.2: Living Room temperatures for the horizontal near-vent case. (Left: Test 1 Pallets; Middle: Test 2 Pallets and OSB; Right: Horizontal Test 3 Furniture)

It should be noted that the peak following initial ventilation varied between the three different fuel packages. In the case of the near vent, the pallets fuel package grew to a new steady state that was fuel-limited, as the ventilation available exceeded the fuel present. This is evident through a decline in temperatures prior to the onset of suppression. The peak temperatures post-ventilation also showed values less than that of the initial peak, pre-ventilation. The environment in the fire room remained stratified with temperatures near the ceiling surpassing 750 °F (398 °C), while temperatures near the floor remained below 250 °F (121 °C).

Adding additional mass in the form of OSB to the fuel package significantly increased the magnitude of temperatures in the room post-ventilation when compared to the fuel package only containing pallets. With OSB, the temperatures in the fire room post-ventilation were greater than that of the initial peak, pre-ventilation. The second peak with OSB is ventilation-limited as temperatures do not begin to decline until after the point of suppression. The environment remained stratified, like the pallets fuel load, where temperatures near the ceiling surpassed 1500 °F (816 °C), while temperatures near the floor remained below 500 °F (260 °C). Comparing the two wood-based fuel packages to the furniture fuel package, also shows different conditions post-ventilation. With the furniture fuel package, regrowth of the fire occurred quicker as temperatures from floor to ceiling increased rapidly as the room approached flashover. Flashover, with uniform floor to ceiling temperatures over 1500 °F (816 °C), was present until suppression.

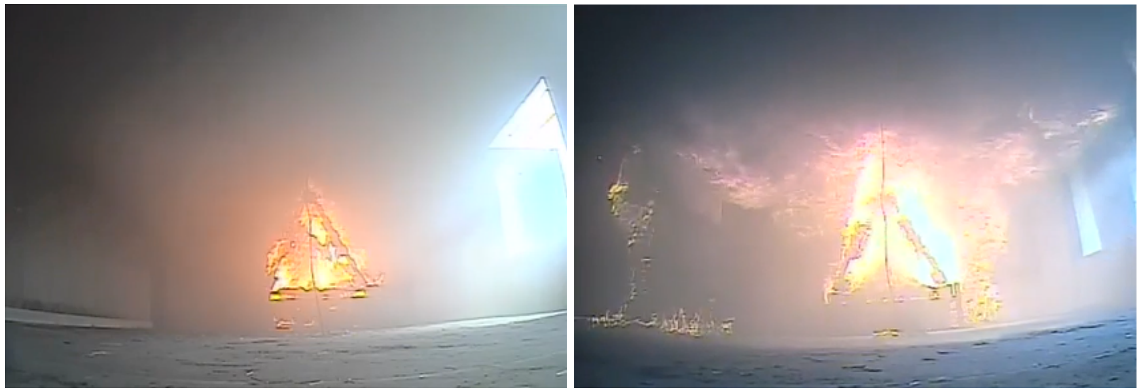


Figure 5.3: Living Room conditions for the horizontal near-vent case after ventilation approximately 30 seconds prior to suppression. (Left: Test 1 Pallets; Right: Test 2 Pallets and OSB)

Figure 5.3 shows the conditions present in the living room approximately 30 seconds prior to suppression. This was after both the front door and living room window were opened and the fire grew to a new steady state. In Test 1 with a pallets fuel package, there is little to no layer evident and a clear visual of the fuel limited conditions present in the compartment as the pallets continue to burn away. In Test 2 with the addition of OSB to the fuel package, there is a distinct layer with flaming combustion throughout the compartment. The fire is ventilation controlled.

Ventilation-limited fire conditions were also seen with the horizontal far vent case. The far vent is reference to the experiments in which the horizontal ventilation opening is made in a remote room, away from the seat of the fire. Figure 5.4 shows similar trends in which an initial peak is present with all vents closed. As the oxygen is depleted, the temperatures begin to fall prior to the front door being opened. After a new source of oxygen is introduced via the front door and window opening, the fires once again, grow to a new steady state.

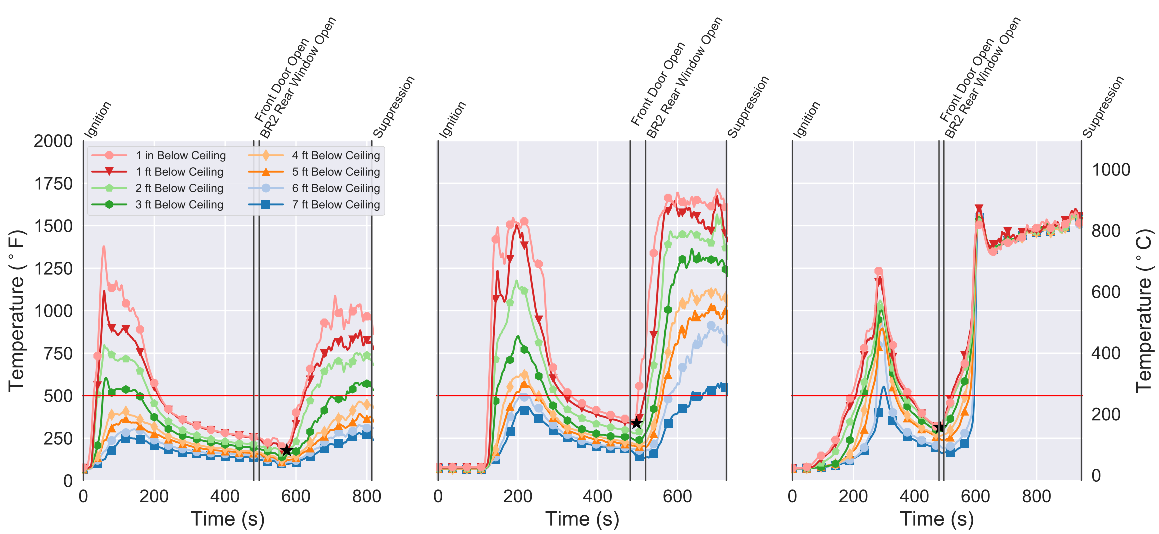


Figure 5.4: Living Room temperatures for the horizontal far-vent case. (Left: Test 3 Pallets; Middle: Test 4 Pallets and OSB; Right: Horizontal Test 7 Furniture)

Much like with the near vent experiments, the new peak post ventilation for the far vent experiments also varied between the three different fuel packages. The Bedroom 2 rear window was the horizontal vent opening for this experiment which was half the size of the Living Room window for the near vent case. The smaller vent opening, located remote from the fire, restricted some of the ability to exhaust heat and products of combustion from the structure. This allowed the temperatures to remain near steady in the experiment until suppression. This was evident for both wood-based and furniture fuel loads. With only pallets, the fire in the Living Room began to regrow, but not until after both the front door and Bedroom 2 rear window were opened. At this point, temperatures began to increase at all levels in the space. The room remained stratified for the duration of the experiment with temperatures near the ceiling reaching 1000 °F (538 °C) while temperatures at the floor remained below 250 °F (121 °C). When compared to the near vent case, the window opening in the fire compartment was large and in close proximity to the fire, which allowed for more efficient combustion. More heat and products of combustion were exhausted as more air was drawn in from the front door. This allowed for the fire in the near vent case to be fuel controlled with the pallets before suppression occurred. Adding fuel mass in the form of OSB, allowed the Living Room temperatures in Experiment 4 to reach over 1500 °F (816 °C) near the ceiling and above 500 °F (260 °C) near the floor. The environment remained stratified and the compartment did not reach flashover. The furniture test grew rapidly to a new steady state after flashing over the compartment. Temperatures were uniform in the space near 1500 °F (816 °C). Regrowth for both the pallets and OSB and furniture fuel loads occurred almost instantly after the front door was opened and both remained ventilation controlled until the onset of suppression.

Because ventilation-limited conditions occur across all three fuel packages tested prior to ventilation (both wood-based and furniture), it is concluded that the "all closed" ventilation profile in combination with the structure type and minimal leakage are contributing factors. Additionally, the fuel package size was sufficient enough to lower the oxygen originally present in the structure and aid in creating these conditions.

If an instructor choses to incorporate ventilation-limited fires into training evolutions, consideration must be given to ensuring all vents within the structure initially remain closed. Leakage throughout the building must be minimal to ensure that the oxygen in the space is able to be depleted. Once the fire enters an initial decay phase, a ventilation opening can be made to show the fuel package response to increased oxygen and growth to a new steady state. Multiple evolutions with ventilation openings made in differing locations, both near to and far from the seat of the fire, can show that the closer the ventilation opening is, the quicker the fire responds and begins to regrow.

5.1.2 Forcing the Front Door is Ventilation

Fireground Tactical Consideration Summary: *Forcing entry has to be thought of as ventilation as well. While forcing entry is necessary to fight the fire it must also trigger the thought that air is being fed to the fire and the clock is ticking before either the fire gets extinguished or it grows until an untenable condition exists jeopardizing the safety of everyone in the structure.* [1]

In the process of trying to create realistic fire dynamics within acquired structures, instructors will often create ventilation openings that are present from ignition, either through open windows and/or open doors. This allows the fire to grow uninhibited by oxygen depletion to as large as possible for the students. Many times instructors will only close the front door shortly before the crew enters in order to ensure the students conduct a proper size-up and practice door procedures (masking up and forcing entry). With pre-existing ventilation openings, the fire may not become ventilation limited with training fuels, as seen during the testing here. Allowing the front door to initially remain closed and then be opened as a part of the training sequence not only helps to replicate ventilation limited conditions, but also shows the students the concept that venting the front door provides the fire a new source of oxygen causing temperatures to rise and conditions to deteriorate as the fire regrows. This response to ventilation is evident with both furniture composed of synthetic materials and foam plastics, as tested previously, as well as wood-based training fuels tested here in acquired structures.

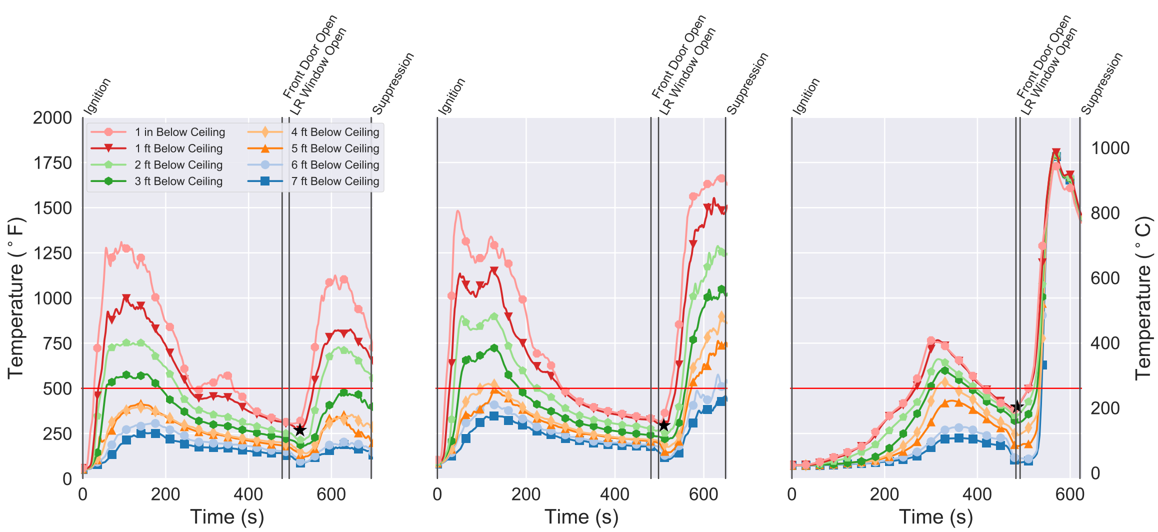


Figure 5.5: Living Room temperatures for the horizontal near-vent case. (Left: Test 1 Pallets; Middle: Test 2 Pallets and OSB; Right: Horizontal Test 3 Furniture)

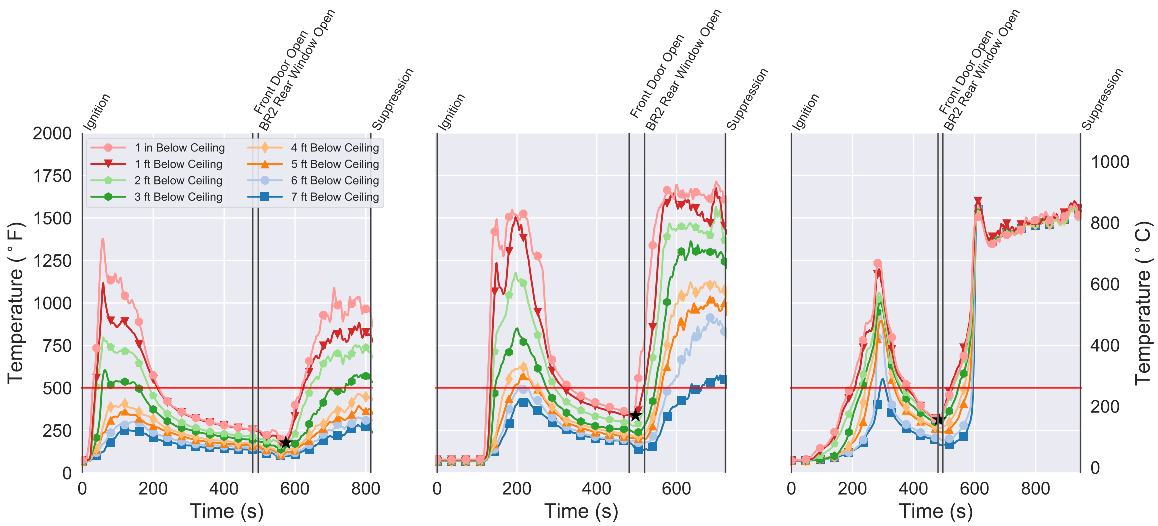


Figure 5.6: Living Room temperatures for the horizontal far-vent case. (Left: Test 3 Pallets; Middle: Test 4 Pallets and OSB; Right: Horizontal Test 7 Furniture)

Both Figures 5.5 and 5.6 show temperature rise as the fire began to regrow within the compartment after the front door and window were opened. It is still a common gap in understanding that an open front door is ventilation. Both during training evolutions and on the fireground, the front door is typically only referenced during forcible entry procedures. The door is simply utilized as a point of reference for entry and not its ability to affect fire behavior within the structure. If training begins to incorporate how the front door, or any ventilation for that matter, can affect fire growth in a compartment, this understanding and associated best practices can be carried over to the fireground.

If the temperatures at 3.0 ft. above the floor are examined from Figures 5.5 and 5.6, the differences in response to the ventilation are clear between the three fuel packages tested. Firefighters operating in the structure for the pallets only scenario would likely not feel the increase in temperatures (which was slower compared to other fuel packages tested) due to the increased ventilation, while in the pallets and OSB scenario, firefighters would feel the increase in temperatures within a short duration as the environment becomes dangerous and untenable. With the furniture scenario, the conditions become deadly within a short period of time as the temperatures increase rapidly with the room flashing over.

Because the event timing for these experiments was such that the window vent was opened very soon after the front door was opened, it is difficult to distinguish that the response to ventilation and subsequent regrowth of the fire can be isolated to the front door alone. Likely, the front door provided a new source of oxygen which began to work its way to the fire, either in the Living Room or rear bedroom (Bedroom 2). By the time the fire began to react to the new source of oxygen, the window was also ventilated and as such, isolating the response to the front door alone is not possible. Regardless of this fact, the front door is another means of horizontal ventilation, just as a window would be, and needs to be considered as such; both in training and on the fireground. In many cases, an open doorway can be a more effective means for the fire to draw fresh air from the outside because the vent goes to the floor whereas a window may be above the neutral plane in the structure and would struggle to serve as both an inlet and exhaust simultaneously.

5.1.3 Nothing Showing Means Nothing

Fireground Tactical Consideration Summary: *A common event during the experiments was that once the fire became ventilation limited the smoke being forced out of the gaps of the houses greatly diminished or stopped all together. No smoke showing during size-up should increase awareness of the potential conditions inside.* [1]

An important size-up clue of ventilation limited fires seen on the fireground today includes the concept of no smoke showing on arrival. Once the fire has grown to its initial peak and enters decay, temperatures inside the structure begin to decline as the fire becomes ventilation limited. Because the volume of the structure is fixed, as the temperatures begin to decline, so does the pressure. As this happens, the atmospheric pressure on the outside of the home becomes higher than the inside as the fire draws air in through openings that were used as an exhaust during the initial growth. While this is occurring, smoke may no longer be evident on the exterior of the structure, leaving arriving firefighters unaware of the extent of the fire within the home.

Ventilation limited fire conditions present dangers for fire crews because openings made for firefighter entry also allow a new source of oxygen to work its way to the fire. Recall from Section 5.1.2, without the proper coordination of timely water application, new sources of oxygen allow for fire regrowth and deterioration of conditions in the structure. Proper training into scene size-up on the fireground would coincide with providing an opportunity for students to see fires grow and become ventilation limited at which time the structure no longer exhibits any smoke showing. This highlights the importance that just because there is nothing evident on arrival doesn't mean there is not a fire present in the structure.

The training fuel horizontal ventilation comparison experiments also presented exterior conditions where no smoke was showing prior to the front door being opened. As the temperatures and pressures dropped within the structure, smoke was no longer visible from the exterior. A snapshot of the video footage and corresponding fire room temperatures in Figures 5.7 and 5.8 captures this phenomenon seen in the exterior view of Side A of the structure.

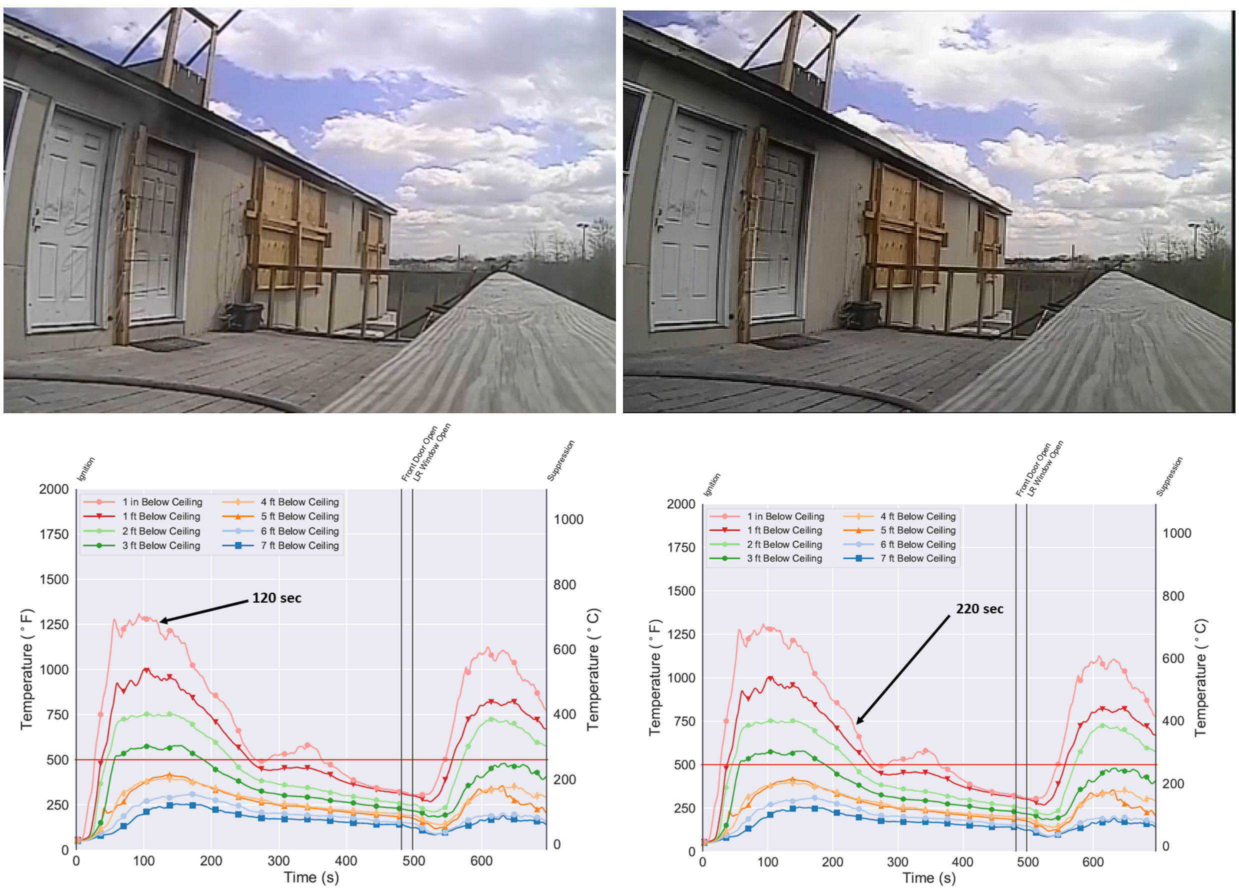


Figure 5.7: Footage and corresponding fire room temperatures in Experiment 1 - Pallets: During Initial Peak (Left) and During Initial Decay (Right). Note very little smoke showing during initial growth with only pallets.

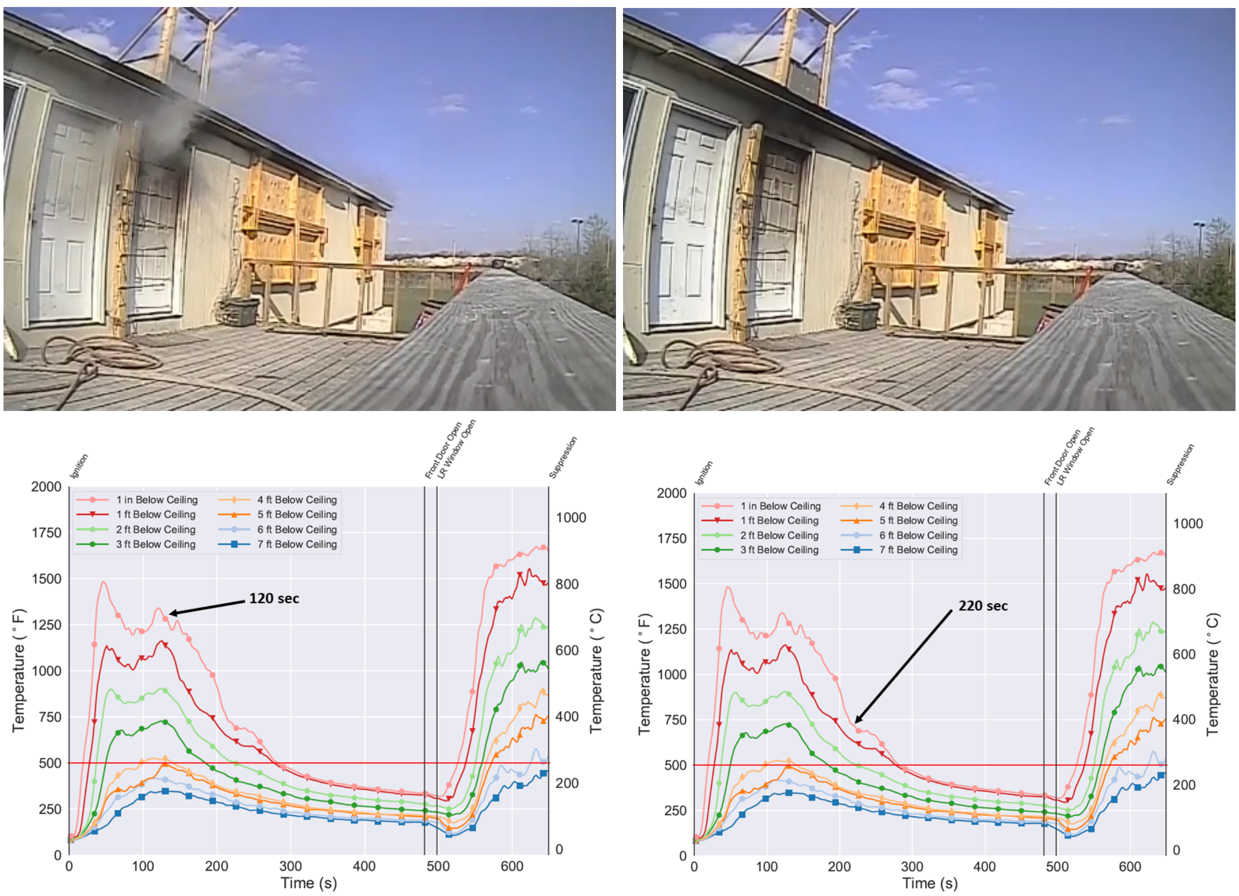


Figure 5.8: Footage and corresponding fire room temperatures in Experiment 2 - Pallets and OSB: During Initial Peak (Left) and During Initial Decay (Right). Note more visible smoke showing during initial growth with the additional fuel mass in the form of OSB.

While the concept of no smoke showing occurred for both training fuel packages, fires consisting of only pallets produced considerably less smoke prior to ventilation. The smoke was lighter in color and less dense, which translated to less smoke showing on the exterior of the structure during the initial growth phase. The additional fuel mass in the form of OSB on the walls and ceiling allowed the fire to involve more of the fuel package prior to transitioning to a ventilation limited state. As such, more smoke was evident from the exterior.

Figure 5.9: Footage of Living Room Visibility During Initial Decay- Pallets (Left) and Pallets and OSB (Right)

One important note is that the smoke generation from wood-based training fuels is substantially different than that of furniture composed of synthetic materials and foam plastics. Take note of conditions within the Living Room of the structure seen in Figure 5.9. Although the temperatures within the space declined as the fire ran out of oxygen, visibility remained relatively clear in the pallets experiment. Smoke production from the pallets experiment appeared less dense and lighter in color. With the addition of OSB, the visibility in the Living Room was more obscured and was a closer representation to that of furniture. This should be highlighted during training to emphasize the difference in products of combustion across the wood-based training fuels when compared to conditions typically found on the fireground.

5.1.4 Coordination of Fire Attack

Fireground Tactical Consideration Summary: *If you add air to the fire and don't apply water in the appropriate time frame the fire gets larger and safety decreases. Examining the times to untenability gives the best case scenario of how coordinated the attack needs to be. Taking the average time for every experiment from the time of ventilation to the time of the onset of firefighter untenability conditions yields 100 seconds for the one-story house and 200 seconds for the two-story house. In many of the experiments from the onset of firefighter untenability until flashover was less than 10 seconds. These times should be treated as being very conservative. If a vent location already exists because the homeowner left a window or door open then the fire is going to respond faster to additional ventilation opening because the temperatures in the house are going to be higher. Coordination of fire attack crew is essential for a positive outcome in today's fire environment.* [1]

It is often discussed that the fireground needs to be coordinated with respect to not only ventilation and suppression tactics, but search and rescue of the structure as well. This concept is also taught on the training ground to show the importance of knowing which actions can occur simultaneously versus which actions need to precede others to ensure a safe operation.

Discussed within the fireground horizontal ventilation study [1] is a hypothetical scenario in which a search team forces open the front door at eight minutes post ignition. The ventilation team opens the front Living Room window at eight minutes and 15 seconds. The search team makes entry and begins to search the Living Room where they notice fire and work their way to the left side of the structure into the Kitchen and Dining Room. This can be seen in Figure 5.10.

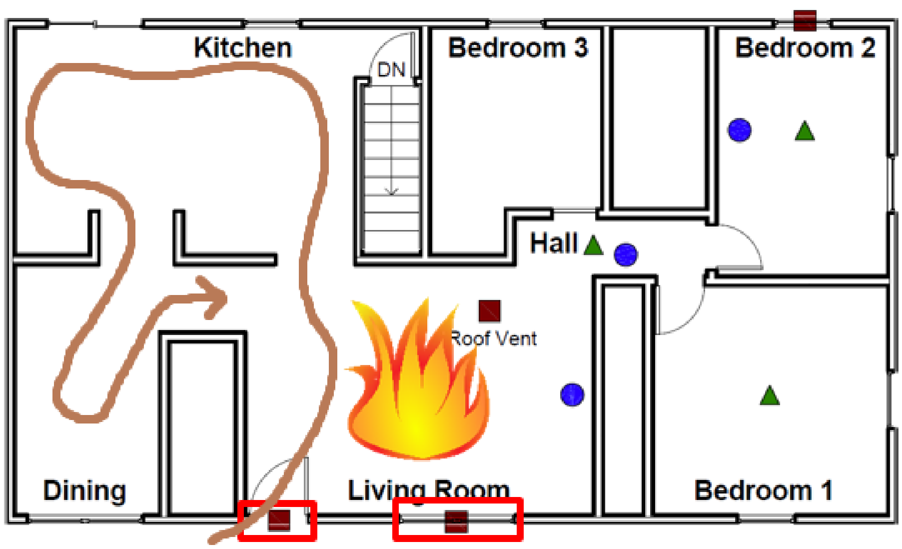


Figure 5.10: Hypothetical search team path as developed during the DHS 2008 Horizontal Ventilation study during the horizontal near vent scenario to discuss the need for fireground coordination.

Two minutes after entry, at 10 minutes after ignition, temperatures within the Living Room are highlighted. With furniture, the temperatures within the Living Room went from tenable upon entry to untenable (500 °F / 260 °C) at firefighter level (3.0 ft / 0.9 m) within two minutes after the front door was opened to make entry. This emphasizes the need to coordinate actions on the fireground and ensure that the search team does not get ahead of water on the fire while other ventilation is taking place, creating new sources of oxygen that aid in fire growth and cause further deterioration of conditions within the structure. Although both scenarios exceeded (500 °F / 260 °C), a firefighter would be able to occupy the space on the order of one to two minutes in the wood-based scenario with OSB versus only seconds with furniture.

For comparison, the representative tests (Experiments 1 and 2) conducted as a part of the training fires study in acquired structures are examined. Both of these wood-based fuel package experiments examined a horizontal ventilation sequence near the seat of the fire. This provides the worst case scenario where the horizontal ventilation opening is made in the fire room and provides the shortest time for the new source of oxygen to reach the seat of the fire. The timing of the sequence matched that of the previous experiment conducted with furniture. Figure 5.11 shows the temperatures measured in the Living Room over the duration of the experiments. The pallets and OSB fuel load in Experiment 2 produced similar peak temperatures near the ceiling post-ventilation that resembled temperatures from the furniture test. While the environment does remain stratified, unlike the furniture experiments which reached flashover, the temperatures in the Living Room during Experiment 2 followed the same trend from tenable to untenable (500 °F / 260 °C) within the two minute period post-ventilation. In Experiment 1 with only pallets, conditions in the Living Room deteriorated after ventilation, but they never reached untenable limits (500 °F / 260 °C) at firefighter level (3.0 ft / 0.9 m) during the experiment.

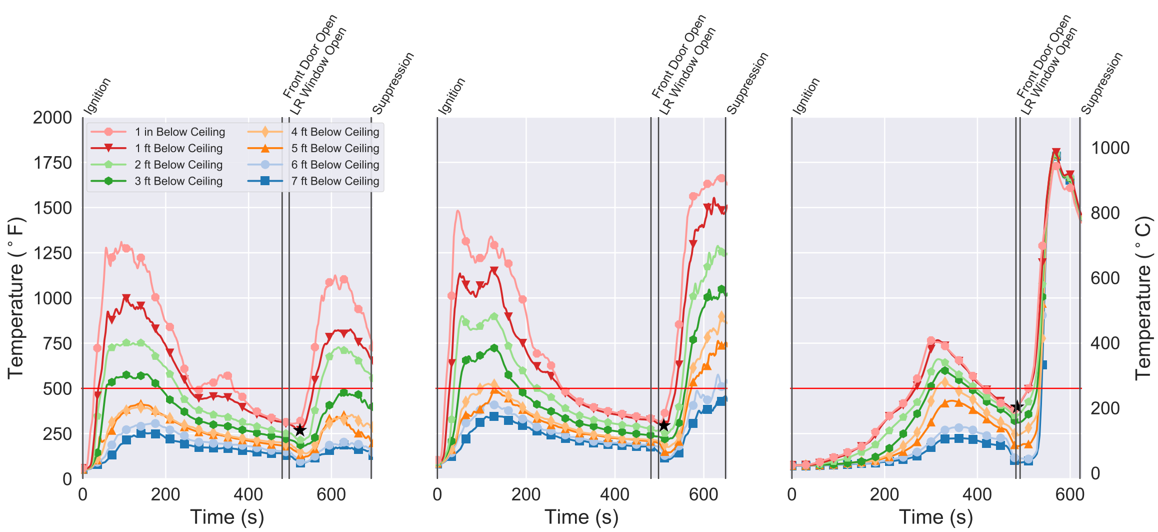


Figure 5.11: Living Room temperatures for the horizontal near-vent case. (Left: Test 1 Pallets; Middle: Test 2 Pallets and OSB; Right: Horizontal Test 3 Furniture)

While both the pallets and OSB and furniture fuel packages reach untenable limits at the firefighter level in the fire room in two minutes post ventilation, the regrowth rate is considerably different between the two. In the furniture experiment, temperatures from floor to ceiling climb rapidly to flashover over the span of seconds. The temperature at 3.0 ft (0.9 m) reaches its peak in just 84 seconds from the time in which the front door was opened. In the pallets and OSB experiment, temperatures are slower to climb, and while they do reach untenable conditions (91 seconds after the front door is opened), the environment remains stratified. The slower growth increases the reaction time for firefighters occupying the space as well as slows down the exposure time in elevated temperatures. Althought both cases reach untenable limits (500 °F / 260 °C), a firefighter may be protected for a longer duration in the training fire with pallets and OSB compared to the furniture fire. This difference should be highlighted of how the training ground may provide a false sense of security compared to the fireground.

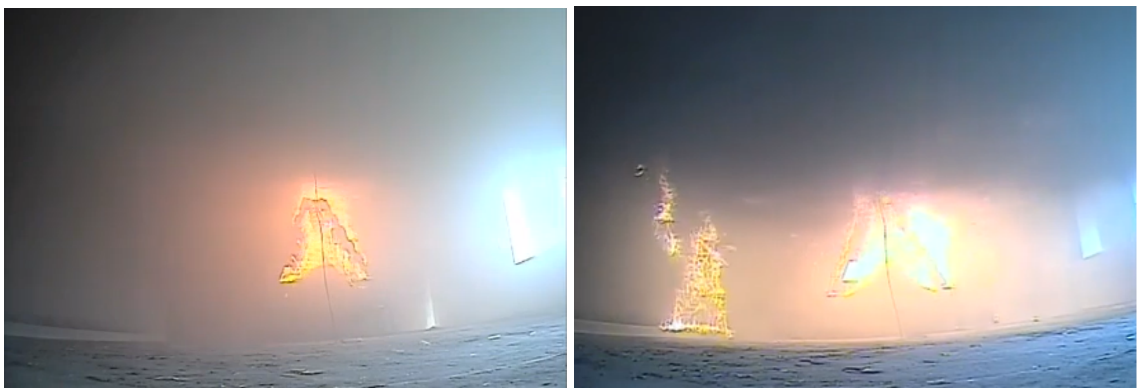


Figure 5.12: Conditions within the living room: one minute post vent (left) and two minutes post vent (right)

In Figure 5.12 showing Experiment 2 with a pallets and OSB fuel package, regrowth was evident within one minute past the Living Room window being opened. At two minutes past the Living Room window being opened, the fire had regrown significantly and fire was evident in the hot gas layer. The amount of time for the simulated crew to exit the structure before saturation of the gear and subsequent burn injury was limited as temperatures continued to rise and conditions continued to deteriorate.

As stated before, the ability to examine the development of a fire with a known fuel load and specific ventilation profile chosen for training is critical prior to student involvement. Instructors should be intimately familiar with how a given fuel package responds to ventilation and suppression tactics prior to conducting live-fire evolutions on the training ground. Conditions that resemble those encountered in the modern fire environment can be produced by wood-based fuel packages as evident with these experiments. Known responses to differing ventilation profiles allows the instructor to create specific evolutions for specific concepts. For example, a pallets and OSB fuel package with all vents initially closed can demonstrate a fire transitioning to a ventilation limited state, the concept of no smoke showing on arrival, and the response to ventilation and uncoordinated suppression leading to regrowth and deterioration of conditions. Some fireground concepts may need to be taught using different fuel packages across various live-fire evolutions in order to maintain a proper balance between safety and realism during training.

5.1.5 Smoke Tunneling and Rapid Air Movement in Through Front Door

Fireground Tactical Consideration Summary: *Once the front door is opened attention should be given to the flow through the front door. A rapid in rush of air or a tunneling effect could indicate a ventilation limited fire.* [1]

As with the experiments conducted during the fireground horizontal ventilation study [1], the smoke layer within the living room in these acquired structure experiments reached the floor prior to the front door being opened. Zero visibility conditions were present throughout the house prior to the first fire service intervention. The concept of smoke tunneling and rapid air movement through the front door was discussed in the previous report regarding horizontal ventilation experiments with furniture, highlighting the fact that the smoke layer did not lift along the flow path between the front door and the seat of the fire after ventilation via the front door. Instead, a better way to describe the impact of ventilating the front door was the presence of smoke tunneling, otherwise known as air intake. This concept was also seen during these experiments with training fuels in acquired structures. Figures 5.13 and 5.14 show snapshots of video footage from two experiments conducted for the horizontal ventilation series.

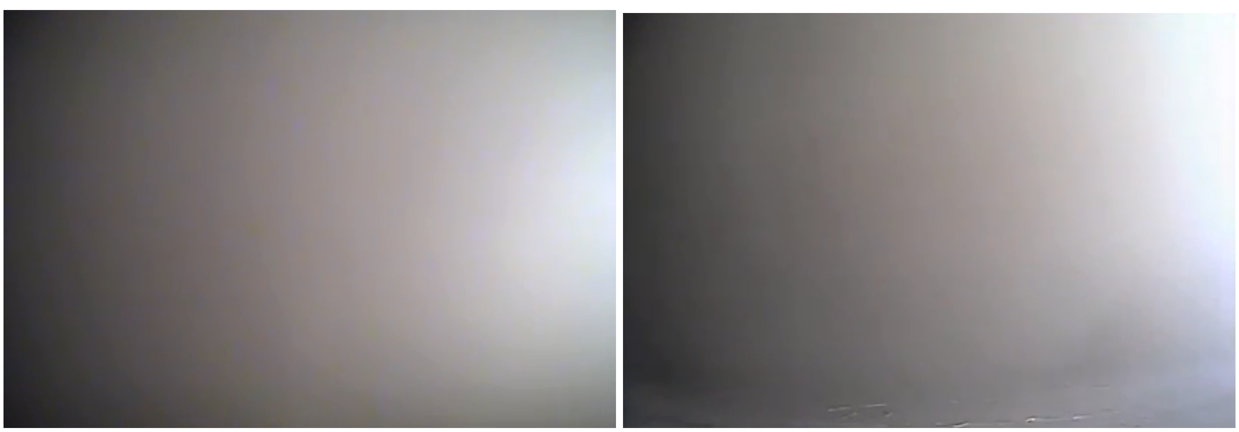


Figure 5.13: Living Room Footage of Experiment 1 with Pallets: five seconds pre-vent (Left) and five seconds post-vent (Right)

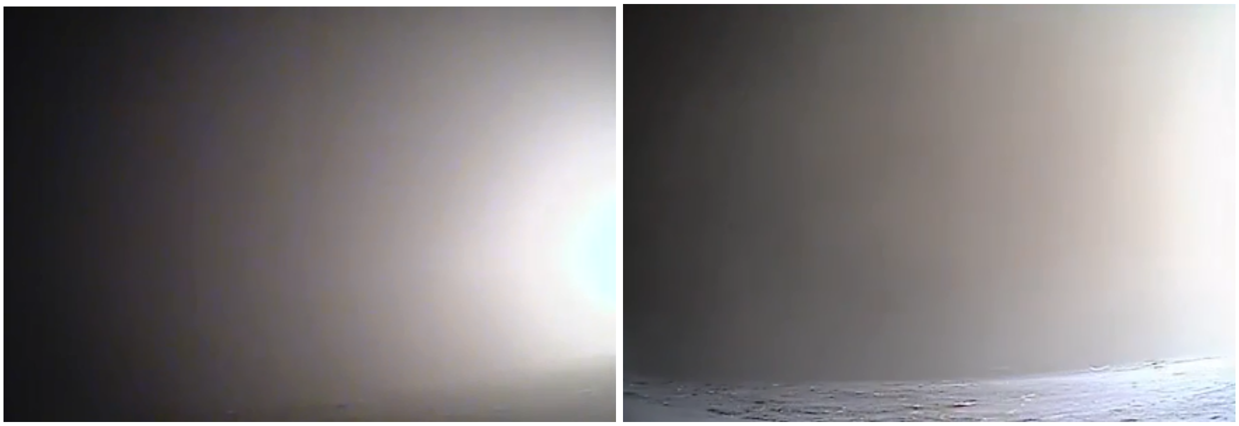


Figure 5.14: Living Room Footage of Experiment 2 with Pallets and OSB: five seconds pre-vent (Left) and five seconds post-vent (Right)

In both experiments, the smoke layer reached the floor, constituting zero visibility, prior to the front door being opened. Looking at the video footage of the fire room at five seconds post ventilation (the right side of each figure), shows the floor now visible as the air rapidly moves into the structure and past the camera. This is footage from the Living Room camera which was positioned adjacent and perpendicular to the front door. The slight lift in the smoke is associated with smoke tunneling as the new source of oxygen is drawn into the structure and to the seat of the fire. This concept is echoed with modern furnishings and is often utilized as a size-up means to help identify the location and possible stage of fire development upon forcing the front door prior to entry.

The gas velocity data presented in Figure 5.15 also confirms the presence of air movement through the front door. Data from the two measurement locations in the front doorway closest to the floor (Bottom Middle and Bottom) show negative flow with the opening of the front door. Negative velocities are indicative of air flowing into the structure. The flow is only moving at 1.0 to 2.0 mph into the structure, but the gas flows are indicative of a bi-directional vent. The top two measurement positions (Top and Top Middle) are showing positive flow as the fire gases exhaust out high in the opening while fresh air is being drawn in low. This occurs across both training fuel packages.

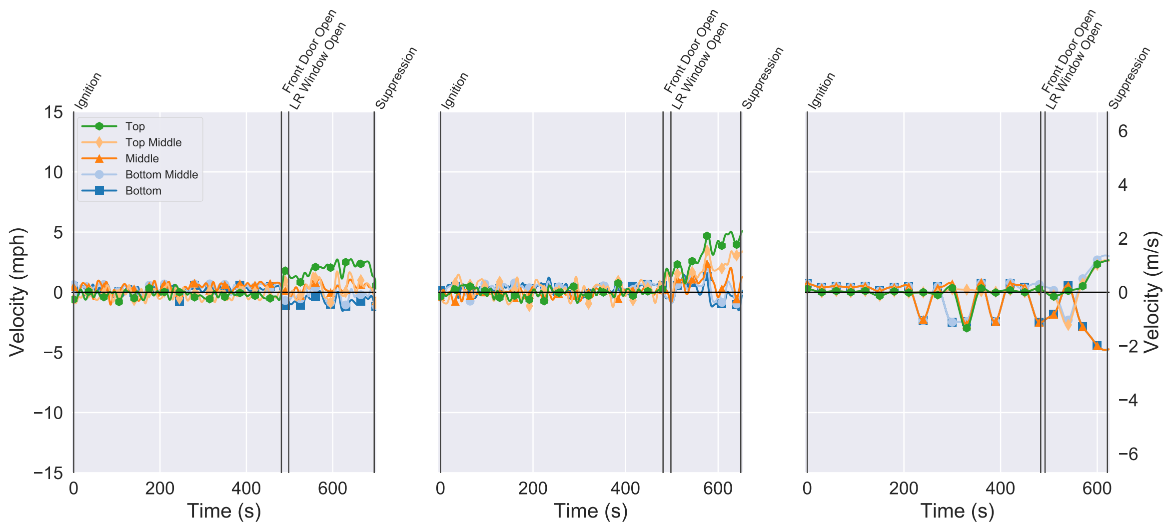


Figure 5.15: Front Door Gas Flows for the horizontal near-vent case. (Left: Test 1 Pallets; Middle: Test 2 Pallets and OSB; Right: Horizontal Test 7 Furniture)

The inrush of air through the front door immediately after ventilation is a potential sign of a ventilation limited fire that is beginning to regrow due to a new source of oxygen and should be shown to students on the training ground as a visual aid in proper size-up procedures prior to making entry into a fire building.

5.1.6 VES — Importance of Isolation

Fireground Tactical Consideration Summary: *During a VES operation, primary importance should be given to closing the door to the room. This eliminates the impact of the open vent and increases tenability for potential occupants and firefighters while the smoke ventilates from the now isolated room.* [1]

As discussed in the Fireground Horizontal Ventilation study, vent-enter-search (VES) or vent-enter-isolate-search (VEIS), is the process of entering a structure through a window and conducting a focused search of the area for potentially trapped occupants. The window of the room of interest may or may not be vented prior to fire department arrival. If it is already open prior to arrival or vented on arrival, the flow path through the interior space is likely established and therefore a rapid change in conditions is less likely. However, it should be noted that although a flow path may be established, conditions within the space may still be considered untenable, even for a firefighter in full protective clothing. On the other hand, if the firefighters conducting the operation have to vent the window for entry, caution should be given to the potential of rapid changes in conditions as the new flow path through the interior space and out the window is established. Depending on the proximity of the fire to the now open vent, conditions may approach untenable limits for potential victims rather quickly. The horizontal ventilation study conducted previously showed the importance of isolating the room as quickly as possible once crew members have entered for the search. Previous experiments exhibited how conditions can worsen within the room if a window remote from the fire is vented, establishing a new flow path from the fire to the window. If the fire is in an under-ventilated state at the time when a VEIS operation would be performed, then isolating the fire from the new source of oxygen is key to improving conditions in the room of interest and preventing the fire from growing and moving towards the new low pressure vent.

The importance of understanding the need behind isolation during a VES operation is evident through examining the far vent horizontal comparison experiments conducted with wood-based training fuels. Each experiment consisted of a fire in the Living Room of the structure where horizontal ventilation was conducted on the Bedroom 2 rear window. Figure 5.16 shows the temperatures measured in Bedroom 2. The ventilation profile consisted of the front door being opened first followed by the rear bedroom window.

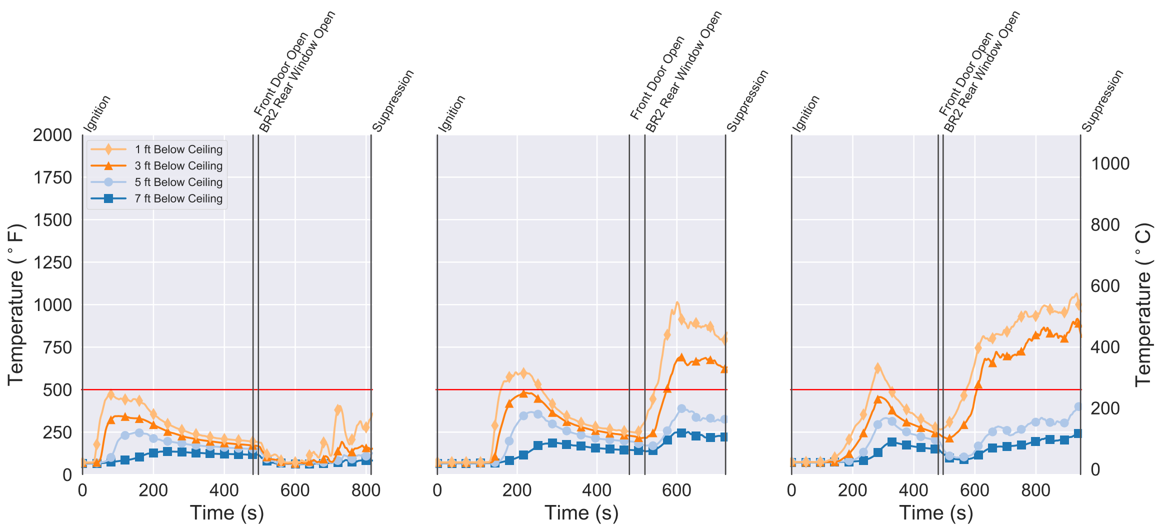


Figure 5.16: Bedroom 2 temperatures for the horizontal far-vent case. (Left: Test 3 Pallets; Middle: Test 4 Pallets and OSB; Right: Horizontal Test 7 Furniture)

The conditions within the rear, remote bedroom varied between the two wood-based training fuel packages. The pallets fuel load created conditions in the bedroom that improved with ventilation initially, which deviated from the results of experiments conducted with furniture during which conditions worsened post ventilation. Additionally, when OSB is added to the pallets fuel load, conditions in the bedroom deteriorated in a similar manner observed during fires with furniture providing a much better representation of the vent-limited fire environment regularly encountered by firefighters today. The wood-based fuel load containing OSB in Experiment 4 showed quicker regrowth in Bedroom 2 when compared to the furniture experiment from the fireground study. If the intent of a live-fire training evolution is to show a vent-enter-search operation in ventilation limited fire conditions, consideration should be given that the pallets fuel package in this vent configuration did not provide an immediate deterioration of conditions in the remote room being searched. This could lead to a false sense of security to the student who is conducting the search when this tactic is employed on the fireground instead of the training ground.

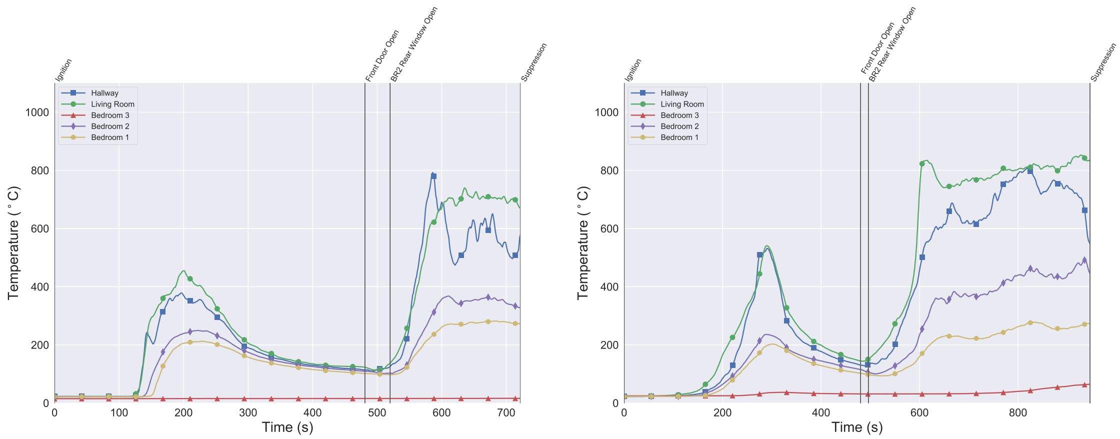


Figure 5.17: Temperatures at 3.0 ft. for the horizontal far-vent case. (Left: Experiment 4 Pallets and OSB; Right: Horizontal Experiment 7 Furniture)

Figure 5.17 shows temperatures throughout the structure at 3.0 ft. above the floor for the horizontal far vent case. The experiment with OSB (left) shows a similar increase in temperatures along the newly developed flow path from the fire to the Bedroom 2 rear window as with furniture (right). Conditions in the Hallway and Bedroom 2 deteriorate relatively quickly at firefighter level, further indicating the importance of isolation as well as the comparison between fire behavior with OSB and furniture. The wood-based fuel package with OSB actually experiences quicker regrowth when compared to furniture.

Care should be given to identify the behavior of a fire with a chosen fuel package, and it's individual response to varying ventilation methods prior to beginning evolutions with student involvement. Utilizing a pallets and OSB fuel load, the response to ventilation was similar to that of furniture in that temperatures within the room began to increase following the opening of the window. Conditions at heights greater than 3.0 ft. above the floor within the space approached and exceeded firefighter tenability (500 °F / 260 °C) within approximately 100 seconds post vent. Temperatures measured one to three feet above the floor approached and exceeded occupant survivability (212 °F / 100 °C) within the same time frame [36]. This highlights the importance of isolating the room from the fire, keeping conditions survivable for any potential trapped occupants and providing firefighters with the time to complete the search.

5.2 Vertical Ventilation

The tactical considerations produced by the previous project titled *Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes* [2] are listed below. The listed items shaded gray were deemed to be outside the scope of this study and therefore are not considered during the comparison of experimental results to the tactical considerations. As discussed in Section 1.2, the number of experiments allotted for vertical ventilation limited the scope and amount of variables able to be tested. Vertical ventilation was limited to the front door and a single roof opening of fixed size, and thus tactical considerations regarding different sized roof openings and manipulation of the front door are not discussed. Additionally, there was not a closed door component to this test, nor was suppression a variable, and as such, these are not discussed as comparisons.

Experiments 5 — 8 with wood-based fuels in acquired structures examined vertical ventilation. Experiments 5 and 9 from the fireground vertical ventilation research [2] conducted previously are utilized as comparisons with similar vent profile and fire location.

Table 5.2: Vertical Ventilation Study Tactical Considerations

Tactical Consideration Title	Section
Modern vs. Legacy Fire Development	5.2.1
Control the Access Door	N/A
Coordinated Attack Includes Vertical Ventilation	5.2.2
How Big of a Hole	N/A
Where Do You Vent	5.2.3
Stages of Fire Growth and Flow Path	5.2.4
Timing is Everything	5.2.5
Reading Smoke	5.2.6
Impact of a Closed Door	N/A
Softening the Target	N/A
You Can't Push Fire	N/A
Big Volume - Apply Water to What is Burning	N/A

5.2.1 Modern vs. Legacy Fire Development

Fireground Tactical Consideration Summary: *The fire service's workplace has changed and one of several significant factors is home furnishings. As compared to legacy furnishings, the modern home furnishings are made of synthetic materials that have significantly higher heat release rates. This shift speeds up the stages of fire development creating an increased potential for ventilation-limited fire conditions prior to fire department arrival. Most importantly, the time between tactical ventilation and flashover are 2 minutes for the modern fire and over 8 minutes in the legacy fire. The legacy fire could be described as forgiving as it pertains to ventilation. The firefighter has time to recover after poorly timed ventilation or an uncoordinated attack as they have approximately 8 minutes to adapt prior to flashover. The time to recover in the modern fire was approximately 2 minutes or 25 % of the legacy time. This data supports the statement that, "You are not fighting your grandfather's fire anymore."* [2]

Vertical ventilation experiments conducted as a part of the previous fireground study highlight the change in home furnishings to include synthetic materials and foam plastics which grow rapidly compared to legacy materials and lead to ventilation-limited conditions, typically prior to fire department arrival on the scene. Additionally, the importance of coordinating ventilation with water application was discussed because of the decrease in time from ventilation to regrowth and subsequent flashover. Quicker regrowth post-ventilation leads to the need for more coordination between crews and an overall less forgiving environment. Comparison experiments utilizing the two wood-based training fuel packages were conducted as a part of this series within the training fires study. For two of the experiments (5 and 6), the fires were in the Living Room of the structure and for the other two experiments (7 and 8), the fire was located in Bedroom 1.

As seen with the horizontal ventilation experiments utilizing wood-based training fuels, similar pre-ventilation behavior was noted with these experiments. The fires in both the Living Room and Bedroom 1 grew to an initial peak consuming the oxygen available for combustion within the structure before entering an initial decay phase, where temperatures began to decline. Figures 5.18 and 5.19 show the fire room temperatures for the near and far vent experiments. The fires in the Living Room experienced a shorter sustained initial peak before entering a decay phase. This is likely due to the fire location and structure compartmentation. The fires in the Living Room were open to the Kitchen, Dining Room, and Hallway which accessed Bedrooms 1 and 2. This allowed for more rapid consumption of the oxygen within the structure when compared to the fires in Bedroom 1. When the fires were located in Bedroom 1, the only path for oxygen to reach the bedroom was through a single, common sized residential doorway which restricted the flow entering and exiting the space. This single opening into the fire room had to serve as both an inlet and an exhaust for the fire as no other vents within the fire room were open. Despite the longer initial peak present in Experiments 7 and 8, the fires still entered into a vent-limited state prior to the front door being opened.

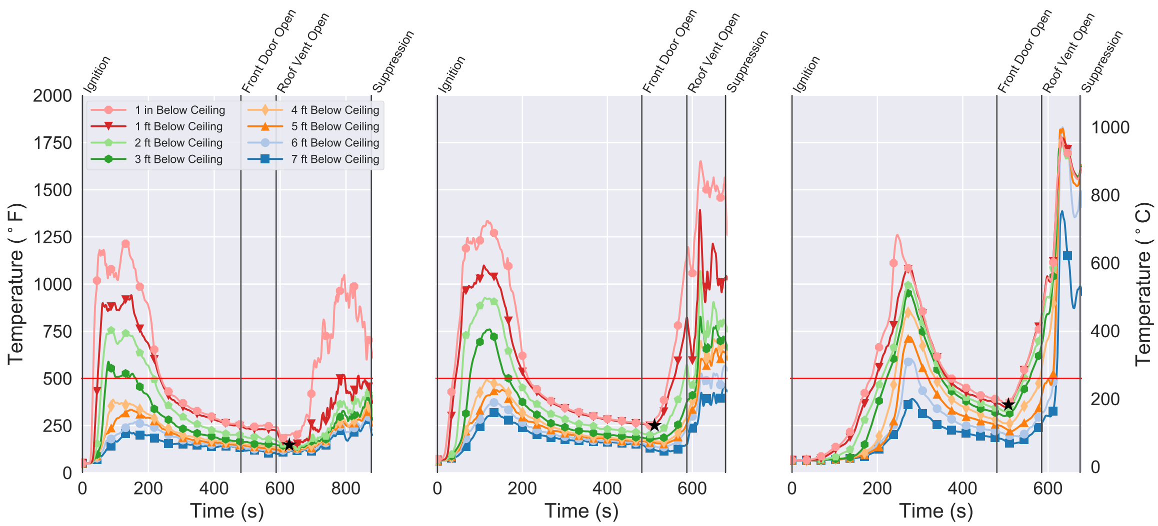


Figure 5.18: Living Room temperatures for the vertical near-vent case. (Left: Test 5 Pallets; Middle: Test 6 Pallets and OSB; Right: Vertical Test 5 Furniture)

After the front door was opened, the response to ventilation varied between the fuel packages tested. In Experiment 5 with pallets, the front door appears to have either no effect or a delayed effect on the Living Room temperatures as they remain steady until the vertical vent above the fire is opened. This could be due to a number of factors including a larger drop in temperatures in the room pre-vent compared to the other fuel packages or due to less burning surfaces higher in the space (OSB) compared to Experiment 6. Once the vertical vent is opened, temperatures near the ceiling drop initially as the fire reacts to the now open vent above the hot gas layer, at the ceiling level. Shortly thereafter, the temperatures begin to rise as regrowth begins in the fire room. The time from the front door open to the beginning of regrowth was 126 seconds. The peak after the ventilation openings were made is short lived and enters a second decay phase prior to the onset of suppression. This indicates that the fire was likely fuel-limited at the peak post-ventilation, just as noted in the horizontal ventilation experiments using only pallets. The pallets fuel load is the smallest of the fuel loads tested and is consumed rather quickly when compared to the pallets and OSB or furniture fuel packages. In Experiment 6 with the addition of OSB, the regrowth begins shortly after the front door is opened. The time from the front door open to the beginning of regrowth was 27 seconds, indicating a quicker response to ventilation when compared to Experiment 5. This is consistent with the vertical ventilation study experiment with furniture used for comparison. During the furniture experiment, the time from front door open to the beginning of regrowth was 18 seconds. Growth continued past the point of opening the roof vent for both the pallets and OSB in addition to the furniture fuel packages. The rate of growth changed slightly with both the front door and roof vent open before attempting to find a new steady state, which remained ventilation controlled until the point of suppression. The Living Room remained stratified post-vent in Experiment 6 with OSB while it reached flashover with the furniture fuel package tested previously.

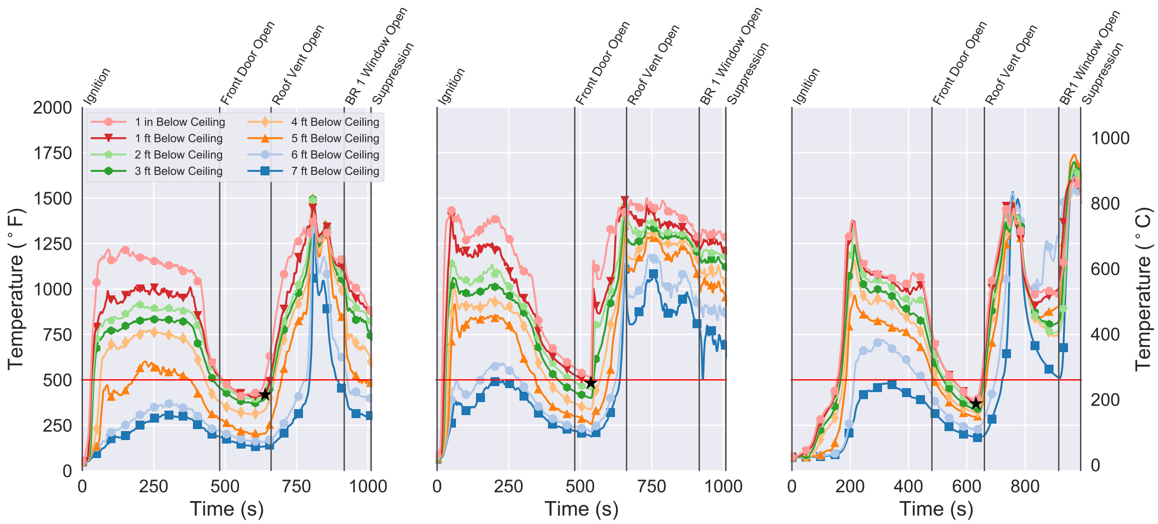


Figure 5.19: Bedroom 1 temperatures for the vertical far-vent case. (Left: Test 7 Pallets; Middle: Test 8 Pallets and OSB; Right: Vertical Test 9 Furniture)

Once the fire was moved to Bedroom 1, the response to ventilation again varied between the fuel packages tested. In Experiment 7 with pallets, the fire began to regrow after the front door was opened, prior to the ventilating the roof. The time from front door open to the beginning of regrowth was 156 seconds. Ventilating the roof appeared to do little to change the growth rate of the fire as temperatures in the bedroom continued to climb. This is likely due to the fact that the vent was no longer above the fire room and was located remote. The second peak in temperatures, post ventilation, is highlighted by a brief moment in which the room experienced flashover until the fuel was consumed. The temperatures near the floor began to climb rapidly after flaming combustion was seen throughout the gas layer in the fire room, as evident in Figure 5.20. After this, temperatures in Bedroom 1 began to re-stratify until the point in which enough fuel was consumed to enter into a fuel limited state of decay. During this, the fire was once again fuel driven, and temperatures began to decline prior to the fire room window being opened. Temperatures continued to decline until the point of suppression.

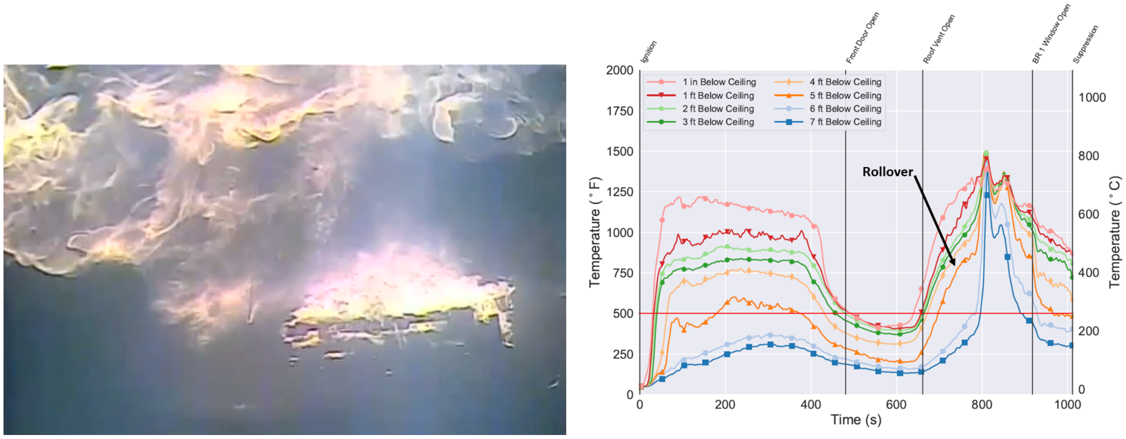


Figure 5.20: Bedroom 1 conditions as the room approached flashover. (Left: Video footage showing rollover; Right: Corresponding temperatures in the bedroom)

The ability of the pallets fuel package to take a room to flashover in an acquired structure is of great importance to an instructor conducting live-fire evolutions. Acquired structures may present unknowns in the form of additional fuels that would not be present in a concrete burn building or metal container located on the grounds of a fire training academy. Live-fire evolutions can be conducted in acquired structures following all of the procedures and guidelines outlined in NFPA 1403 and still create unpredictable fire behavior if the instructors do not account for all of the potential fuels aside from the prescribed fuel package. In this case, the structure was previously used for other fire testing and a public fire safety demonstration, in which the home was painted with several coats to mimic the finish that would be present in the modern day residential home. The build up of paint on the walls of the fire room began to pyrolyze and contribute to the fuel load, providing enough additional burning fuel to transition the compartment to flashover before becoming fuel-limited. If this was not anticipated and students were located either in the fire room or adjacent hallway, the rapid increase in temperatures would have placed the firefighters in a place of danger as tenable limits were surpassed with little time to react.

Experiment 8 which added OSB experienced quicker regrowth when compared to both the pallets and the furniture fuel package. Temperatures at the ceiling began to increase in just 56 seconds, once oxygen made it from the front door to the seat of the fire in Bedroom 1. Temperatures near the floor of the fire room climbed steadily as well. Once the roof vent was opened, the fire room temperatures reached a new steady state. With little to no fuel on the floor, temperatures remained stratified and the room did not exhibit flashover. After the fire room window was opened, temperatures fell slightly to a new steady state before suppression occurred. Comparing these wood-based fuel packages to furniture shows that the furniture had enough unburned fuel to take the room to flashover with the front door and roof vent open. Additionally, once the fire room window was opened, the room flashed over again and reached a new, higher steady state before suppression occurred.

The wood-based fuel packages tested here within acquired structures have both similarities and differences to furniture tested in same structure. All fuel packages reached vent-limited conditions prior to the front door being opened. The response to ventilation was different across the fuel packages and fire locations within the structure. Regardless of the differences, live-fire training evolutions conducted in the same manner as these experiments have the potential to show students ventilation limited fires and the impact of ventilation location on regrowth. Care should be given to understanding that acquired structures can present unknowns in the form of additional fuels which may drastically alter fire behavior in the structure.

5.2.2 Coordinated Attack Includes Vertical Ventilation

Fireground Tactical Consideration Summary: *"Taking the lid off" does not guarantee positive results. Vertical ventilation is the most efficient type of natural ventilation. While it allows the largest amount of hot gases to exit the structure, it also allows the most air to be entrained into the structure. Coordination of vertical ventilation must occur with fire attack just like with horizontal ventilation. The way to make sure that the fire does not get larger and that ventilation works as intended is to take the fire from ventilation-limited (needs air to grow) to fuel-limited by applying water. As soon as the water has the upper hand (more energy is being absorbed by the water than is being created by the fire), ventilation will begin to work as intended. With vertical ventilation this will happen faster than with horizontal ventilation assuming similar vent sizes.* [2]

Much like with horizontal ventilation, the coordination of vertical ventilation with water application is key. As shown previously in Section 5.2.1, regrowth occurs shortly after a ventilation opening is made. This occurs with both the front door and the vertical vent. It also occurs whether the fire is located in the Living Room with the vertical vent above the seat of the fire or with the fire in Bedroom 1 and the vertical vent located remote from the seat of the fire. This behavior is consistent across both wood-based training fuel packages in addition to furniture tested previously.

Considering the same hypothetical search scenario as in Section 5.1.4, the front door is opened by arriving firefighters. A team of firefighters enters and proceeds to conduct a left-hand search, passing through the Living Room into the Kitchen and Dining Room. See Figure 5.21. Conditions in the structure after the vertical vent was made are examined. This discussion only pertains to Experiments 5 and 6 in which the fire was in the Living Room and the vertical vent was made directly above the fire. During experiments 7 and 8, the fire was located in Bedroom 1. While the conditions in Bedroom 1 did become untenable, the impact to the rest of the structure was limited because of the single restricted door opening into the room. The scenario pertains to a fire in the Living Room due to the proximity to the front door and the fire being located in an area which is open to a majority of the rest of the structure. Because suppression in Experiment 6 occurred before two minutes post vertical vent, conditions are evaluated at one minute post vertical vent.

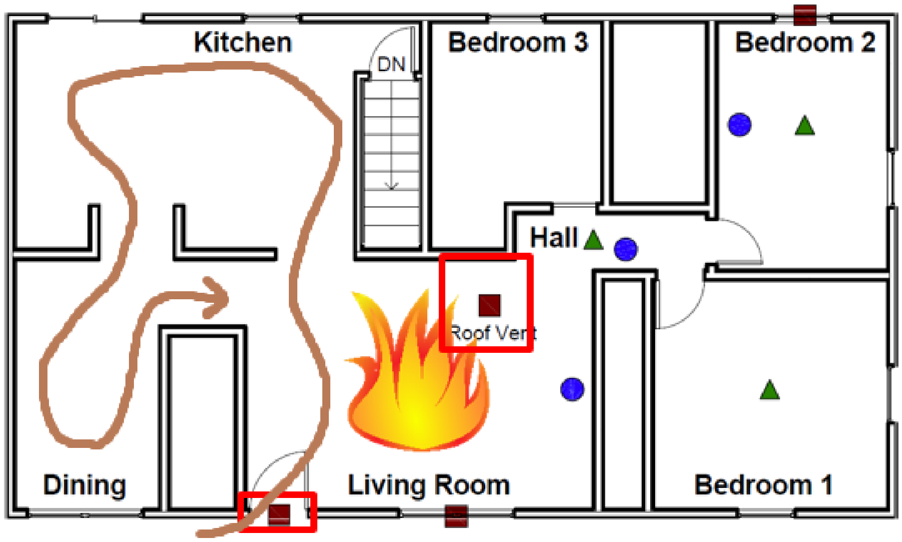


Figure 5.21: Hypothetical search team path during the vertical near vent scenario to discuss the need for fireground coordination.

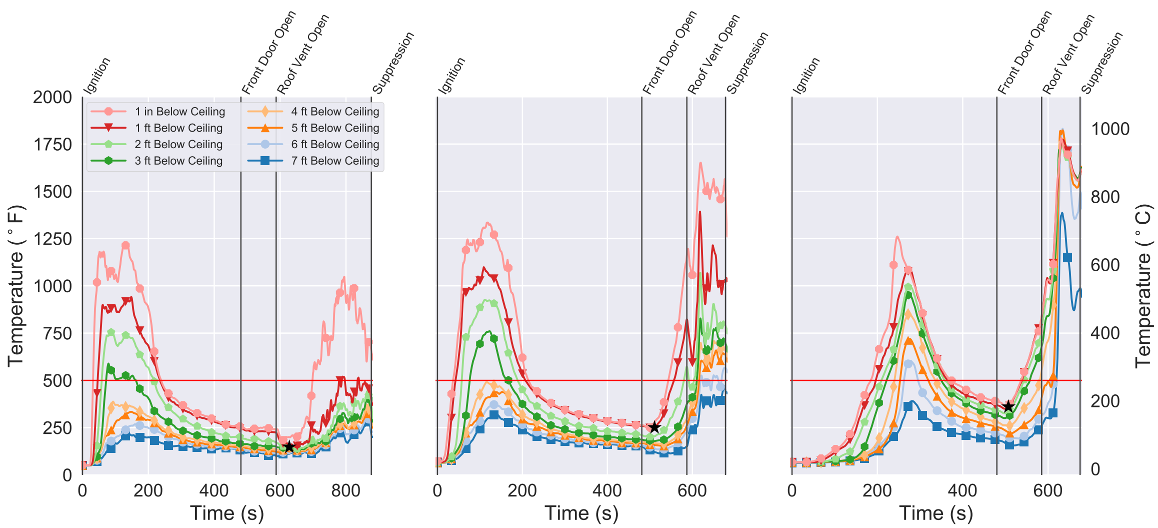


Figure 5.22: Living Room temperatures for the vertical near-vent case. (Left: Test 5 Pallets; Middle: Test 6 Pallets and OSB; Right: Vertical Test 5 Furniture)

Without the coordination of water application with the vertical vent, conditions within the structure deteriorate as the fire regrows. The temperatures begin to rise as the fire grows which causes an increase in smoke production as well as a decrease in visibility. If the search crew were to follow the path shown in Figure 5.21, proceeding through the Living Room to the Kitchen and Dining Room, their path back to the front door would be cut off by fire conditions. With the exception of the pallets fuel package, conditions at one minute post vertical vent are beyond untenable limits at firefighter level within the Living Room for the pallets and OSB in addition to the furniture fuel packages (Figure 5.22). Temperatures in the Living Room at firefighter level reach 500 °F (260 °C) in 135 seconds after the front door was opened. In the experiment with furniture, temperatures in the Living Room at firefighter level reach 500 °F (260 °C) in 131 seconds after the front door was opened.

Figure 5.23: Living Room conditions one minute after the roof vent was opened above the fire. (Left: Test 5 Pallets; Right: Test 6 Pallets and OSB)

The difference in response to vertical ventilation for the wood-based training fuels needs to be highlighted with respect to training evolutions. Conditions in the Living Room varied drastically between the pallets fuel package when compared to the pallets and OSB fuel package. Figure 5.23 presents snapshots of the conditions found in the Living Room at one minute after the vertical vent has been opened. Experiment 5 with only pallets (left image in Figure 5.23) shows the fuel limited conditions found in the Living Room post vertical vent. A crew conducting search and rescue training in this experiment would have been exposed to less severe conditions than that of Experiment 6 with the addition of OSB to the fuel package. In Experiment 6, at one minute post vertical vent, the conditions in the Living Room are untenable at firefighter level. Flaming combustion is seen in the gas layer throughout the room as oxygen from the open front door enhances burning (right image in Figure 5.23). While the room did not experience flashover, any firefighters operating near to the fire would still have limited time to make it to the front door before heat transfers through their gear resulting in a potential injury.

With the additional ventilation in the form of a vertical opening through the roof structure allowing fire gases to exhaust up and out, the front door became an inlet for oxygen to make its way to the seat of the fire. This enabled an increased burning rate and more efficient burning. Figures 5.24 and 5.25 shows the gas velocities at the front door of the structure.

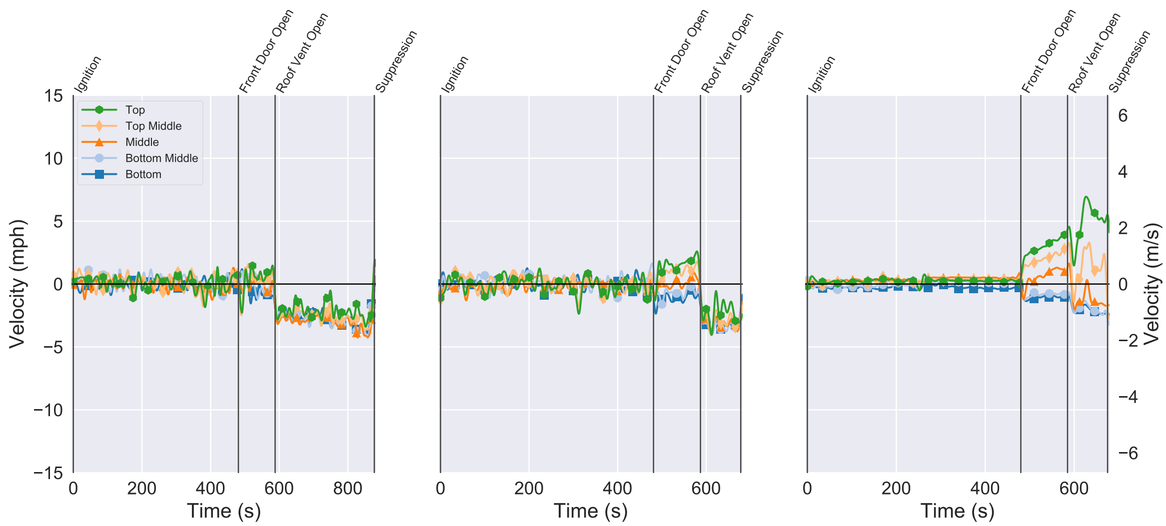


Figure 5.24: Front door gas velocities for the vertical near-vent case. (Left: Test 5 Pallets; Middle: Test 6 Pallets and OSB; Right: Vertical Test 5 Furniture)

When the fire is located in the Living Room (Figure 5.24), the gas velocities at the front door showed varying responses to the roof vent. With wood-based training fuels, the front door transitioned from bi-directional flow to uni-directional flow into the structure once the roof vent was opened. This is evident by the negative flow at the door in Figure 5.24. The furniture fuel package regrew and took the Living Room to flashover. Because of this, the roof vent was not capable of exhausting the increased fire size, and thus, the front door remained bi-directional flow throughout the experiment. With the wood-based fuel load, the roof vent was capable of exhausting the products of combustion from the increased burning and the front door remained all inflow. This discrepancy between wood-based training fuels and furniture needs to be highlighted to show that without proper coordination, the furniture fuel loading found on the fire ground can quickly overcome the vertical ventilation and deteriorate conditions throughout the rest of the structure until water is applied. The overall fuel mass and subsequent heat release rate of the furniture fuel package was the highest of the three fuels tested and contributed to these differences. This is an instance in which the training ground cannot replicate the fire ground and may create misunderstanding of the effectiveness of vertical ventilation in certain scenarios if not explained appropriately.

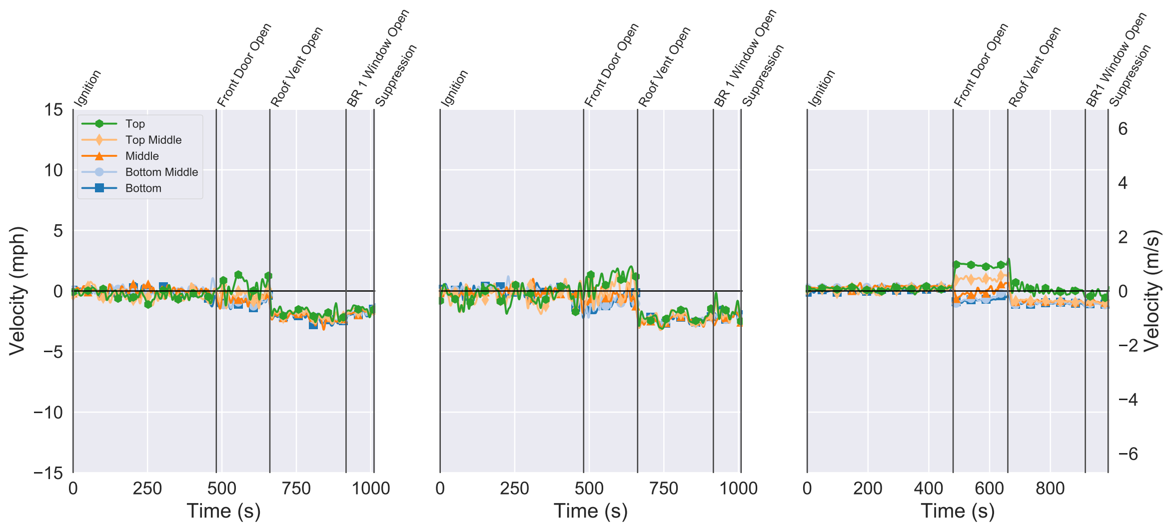


Figure 5.25: Front door gas velocities for the vertical far-vent case. (Left: Test 7 Pallets; Middle: Test 8 Pallets and OSB; Right: Vertical Test 9 Furniture)

With the fire located in Bedroom 1 (Figure 5.25), gas velocities at the front door showed a similar response to the roof vent being opened regardless of whether the fuel package was wood-based or furniture. The front door served as both an inlet and exhaust when it was the only vent present in the structure. As the roof vent was opened, the front door transitioned to uni-directional inflow for the wood-based fuel loads. Even though the fire room regrew to flashover with furniture, the constricted flow through the bedroom doorway allowed the vertical vent to continue to exhaust the majority of the fire gases. Slight outflow from the upper portion of the front door was evident with furniture highlighting the increased fire size present with this larger fuel package.

Live-fire training evolutions with vertical ventilation should incorporate water application, highlighting the importance of coordination between the tactics. The water application will take the fire from a ventilation limited to a fuel limited state and allow the vertical vent to work as intended, removing heat and fire gases from the structure allowing for easier knockdown and search capabilities. If the water application is not coordinated with the vertical ventilation opening, the

5.2.3 Where Do You Vent?

Fireground Tactical Consideration Summary: *Ventilating over the fire is the best choice if your fire attack is coordinated. The closer the source of the air to the seat of the fire, the quicker it will increase in size. Placement of vertical ventilation can be a complex situation, especially if you do not know where the fire is in the house. Optimally, where you vertically ventilate depends on the room geometry, door locations, air inlet location, and subsequent flow paths. If you ventilate in coordination with fire attack (the hose stream is removing more energy than is being created), then it does not matter where you ventilate, but the closer to the seat of the fire, the more efficient the vent will be in removing heat and smoke, which will improve conditions for the remainder of the operations taking place on the fire ground. Ventilating remote from the fire can be effective under some circumstances. If the fire is in a room that is connected to the rest of the house by a doorway, ventilating the roof outside of that room could allow for smoke to be cleared from the rest of the house. However, as air is entrained to the room, fire will increase in size, while visibility may improve in the flow path leading from the air inlet to the fire room. The vertical ventilation may improve visibility even though the fire may grow and local temperatures may increase.* [2]

The previous vertical ventilation experiments with furniture analyzing vent location determined that if the fire attack is coordinated, then venting over the fire room is the most effective. The near simultaneous water application with vertical ventilation transitions the fire from a ventilation limited to a fuel limited state. A vent made directly above the fire allows the heat and fire gases to exhaust the quickest, with the vent remaining capable of handling the fire size. With timely water application, the fire regrowth is limited and the vertical vent works as intended.

When the fire location is remote from the vertical vent and is confined to a room with a restricted door opening, the response to vertical ventilation is very similar to the scenario in which the vent is directly above the fire. This occurs with both wood-based and furniture fuel packages. Without the restricted opening, a fire remote from the vertical vent would continue to regrow until water application and likely overwhelm the vent along with increasing damage along the flow path from the fire to the vent. Figures 5.26 and 5.27 show the Hallway temperatures for both near and remote vertical vent experiments.

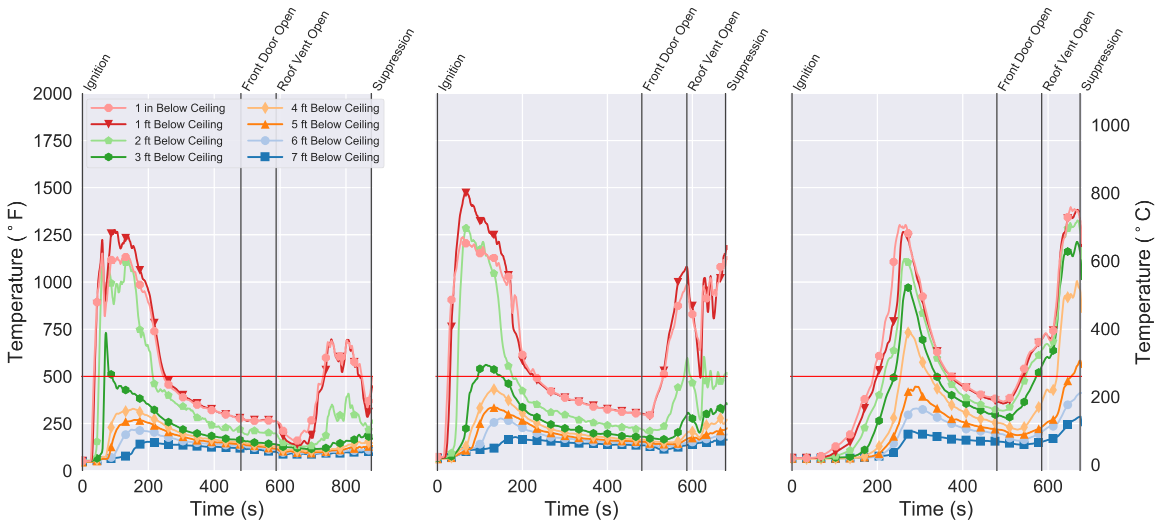


Figure 5.26: Hallway temperatures for the vertical near-vent case. (Left: Test 5 Pallets; Middle: Test 6 Pallets and OSB; Right: Vertical Test 5 Furniture)

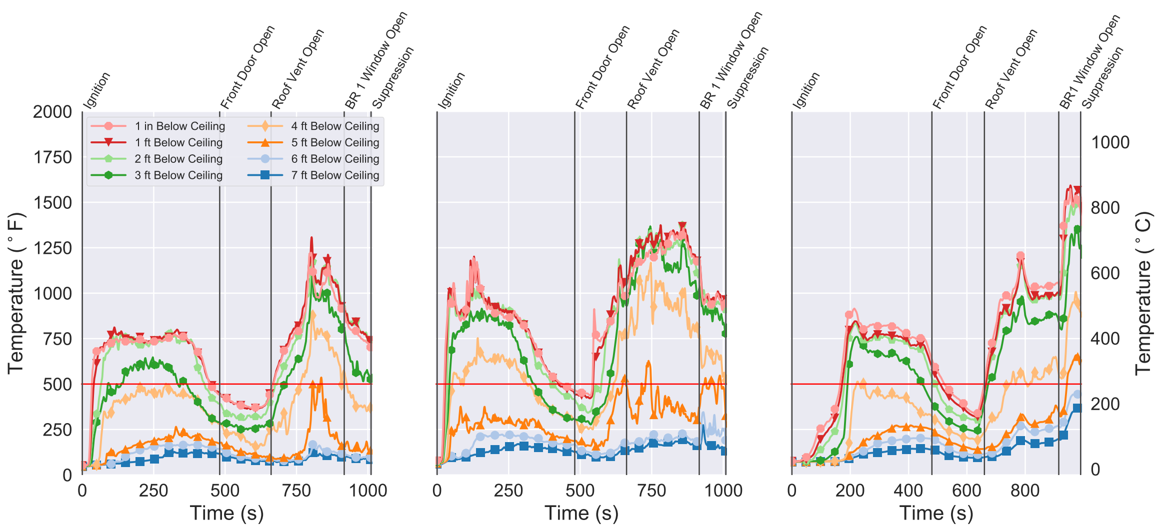


Figure 5.27: Hallway temperatures for the vertical far-vent case. (Left: Test 7 Pallets; Middle: Test 8 Pallets and OSB; Right: Vertical Test 9 Furniture)

Figure 5.27 shows the Hallway temperatures in the experiments where the fire was located in Bedroom 1 with the vertical vent, located remote, above the Living Room. Temperatures in the Hallway were higher after the roof vent was opened when compared to the near vent case (Figure 5.26). This supports the idea that the Bedroom 1 fire continued to regrow after the vertical vent was opened and both deteriorated conditions and increased damage along the flow path from Bedroom 1 to the Living Room, where the vent was located. Additionally, the Hallway in the remote vent case was located in the flow path and likely contributed to the higher temperatures. The restricted opening into Bedroom 1 allowed the vertical vent to exhaust the gases effectively (no outflow through the front door) from the increased fire size even though the conditions within the flow path were continuing to deteriorate as temperatures climbed. If an interior attack is chosen, either on the training ground or fireground, the conditions in the flow path on approach may be more severe than that of the scenario where the vertical vent is located directly above the fire. In Figure 5.26, the temperatures in the Hallway show an increase post ventilation near the ceiling level (1 ft or less below the ceiling). This highlights the fire regrowth in the Living Room but also shows that the vertical ventilation opening is working as intended and limiting spread into areas adjacent to the fire room because temperature increase at the lower levels in the space is minimal. This only occurs with wood-based training fuels tested here. With furniture tested previously, temperatures in the Hallway, and even in Bedroom 1, show an increase at all levels in the space right up until suppression. The Hallway and Bedroom 1 were outside of the flow path which emphasizes a discrepancy between training and the fireground. In training, conditions outside the flow path did not deteriorate in the same manner as the experiments with furniture. Consideration should be given to the location of students and instructors in the fire building during live-fire training. Areas that are safe and tenable during training may not translate to the fireground.

In these experiments, the wood-based training fuel packages did not produce enough energy to overwhelm the roof vent, even when the fire was located in the Living Room, immediately adjacent to the front door. This should be highlighted because even though regrowth occurred, the vertical vent remained effective at removing the smoke and hot gases until suppression without a change in flow at the front door (no fire evident out the front door) for the approach of the attack team. With the experiment testing furniture, the Living Room regrew until flashover and quickly overcame the roof vent. Without coordinated water application, this would be considered a negative response to ventilation. Highlighting the difference in available energy between live-fire training with wood-based fuel packages and the fireground with furniture helps to bridge the gap between understanding what tactics are effective in training scenarios versus the fireground.

5.2.4 Stages of Fire Growth and Flow Paths

Fireground Tactical Consideration Summary: *The stage of the fire (i.e., ventilation or fuel limited), the distance from the inlet (door or window) air to the fire, the distance from the fire to the outlet (door, window, roof vent), the shape of the inlet and outlet, and the type and shape of items (furniture or walls) or openings (interior doors) in the flow paths all play key roles in the availability of oxygen to the fire, and ultimately firefighter safety. Operations conducted in the exhaust portion of the flow path can place firefighters at significant risk due to the increased flow of fire, heat, and smoke toward their position.* [2]

As defined in the previous research, a flow path is the volume inside a structure between the fire and a ventilation opening which allows for the movement of heat and products of combustion from the higher pressure fire area to lower pressure areas both inside and outside of the building [2]. Depending on how the structure is configured, including interior compartmentation and specific ventilation profile, there may be multiple flow paths present at any given time. The flow path size and complexity in addition to whether the fire is fuel or ventilation driven are key factors in determining how the fire will respond to ventilation. This is true for both the fireground with synthetic furnishings and the training ground with wood-based fuels. Figure 5.28 shows one potential growth curve for a compartment fire incorporating vertical ventilation. This curve was developed through examining compartment fires with synthetic furnishings.

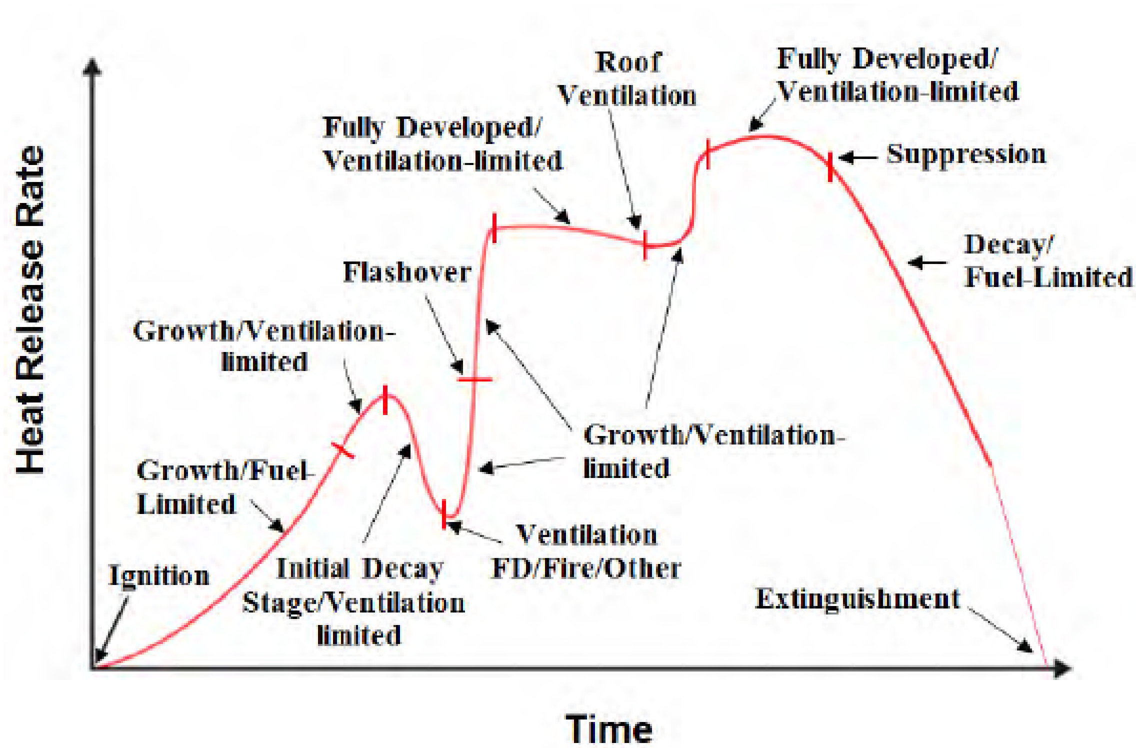


Figure 5.28: Fire growth curve for compartment fire incorporating vertical ventilation.

With respect to compartment fires involving wood-based training fuels, the growth stages follow much of the same trend. Shown below are a series of figures for Experiment 5. Experiment 5 was conducted with a pallets fuel package in the Living Room and incorporated the vertical vent above the fire. The ventilation sequence for this experiment began with all exterior vents closed. At eight minutes past ignition the front door was opened, followed by a vertical ventilation opening directly above the fire one minute and 45 seconds later. Each figure shows the stage of fire growth and corresponding fire room temperatures at different points in time during the experiment. Experiment 5 was chosen as an example; however, each vertical ventilation experiment with wood-based training fuels could have been used to show the same principles. These figures will be used to discuss the stages of fire development and flow paths for this specific case.

Once ignited, a period of growth began where the fire was fuel limited (Figure 5.29). This was not due to a lack of fuel, but instead, the fact that all of the fuel was not yet involved. The fire had enough oxygen to support combustion and the fire continued to grow (Figure 5.30). This was the initial growth stage. Because the fire was located in a compartment, the smoke layer began to descend and eventually reached the level of the burning fuel. While this was still considered the growth stage, the fire now became ventilation limited and the growth rate slowed (Figure 5.31). As oxygen needed for combustion continued to be consumed, less was available due to mixing with the descending layer. Because the fires started with all exterior vents closed, the fire consumed enough oxygen in the structure that combustion was significantly decreased. This corresponded to a decrease in temperatures throughout. Visibility at this stage was completely obscured (Figure 5.32). Up until this point, the flow path was all internal to the structure. No exterior vents were open for the initial growth and decay of the fire. The only access to the outside environment would have been through any available leakage in the structure. The higher pressure fire area (Living Room) would have been moving heat and products of combustion into other rooms in the structure which were of lower pressure. At the point in which the oxygen needed for combustion was depleted and temperatures and pressures declined, the exterior of the structure often stopped showing signs of a fire. This is because the fire area becomes a lower pressure than the outside as it draws air from anywhere possible. As discussed in Section 5.1.3, smoke showing changing to nothing showing should be a sign to help crews identify a ventilation limited fire condition in which the fire may react rapidly to a new source of oxygen.

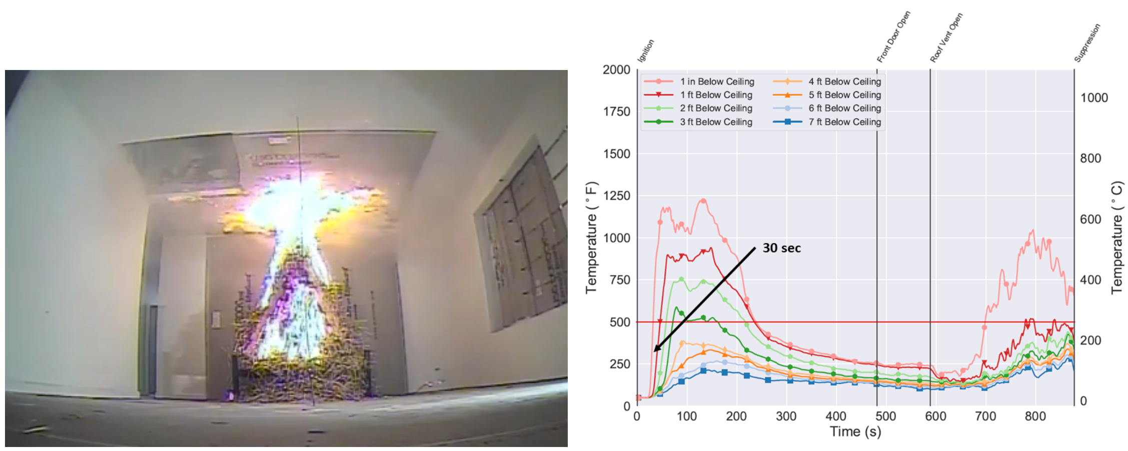


Figure 5.29: Living Room conditions 30 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

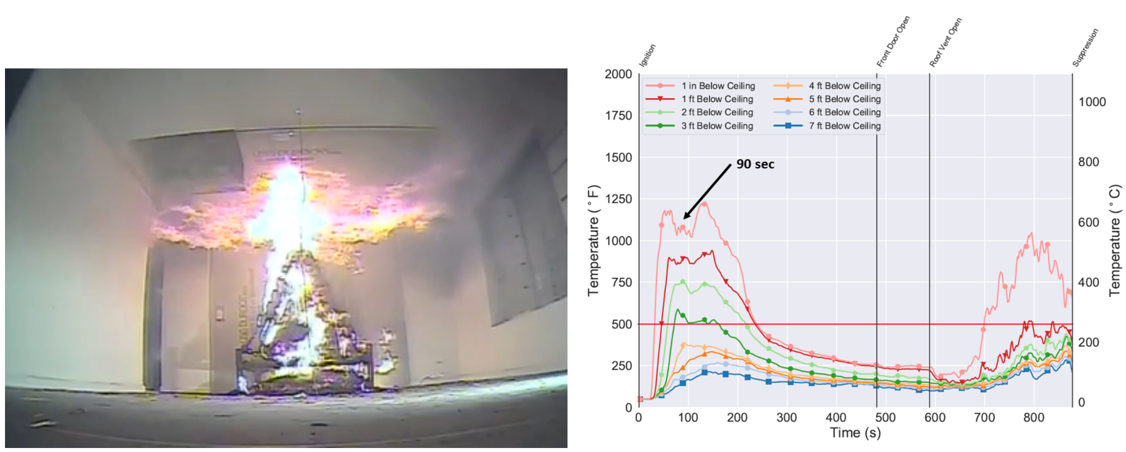


Figure 5.30: Living Room conditions 90 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

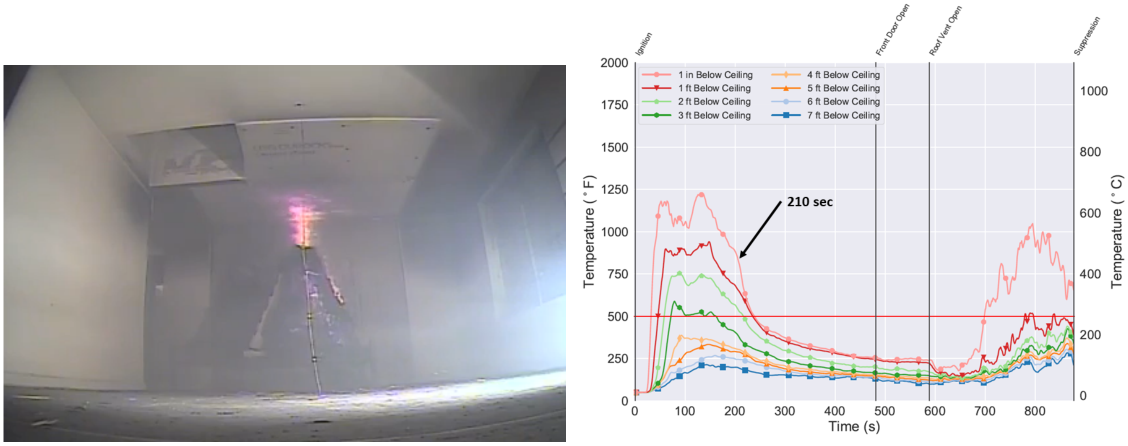


Figure 5.31: Living Room conditions 210 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

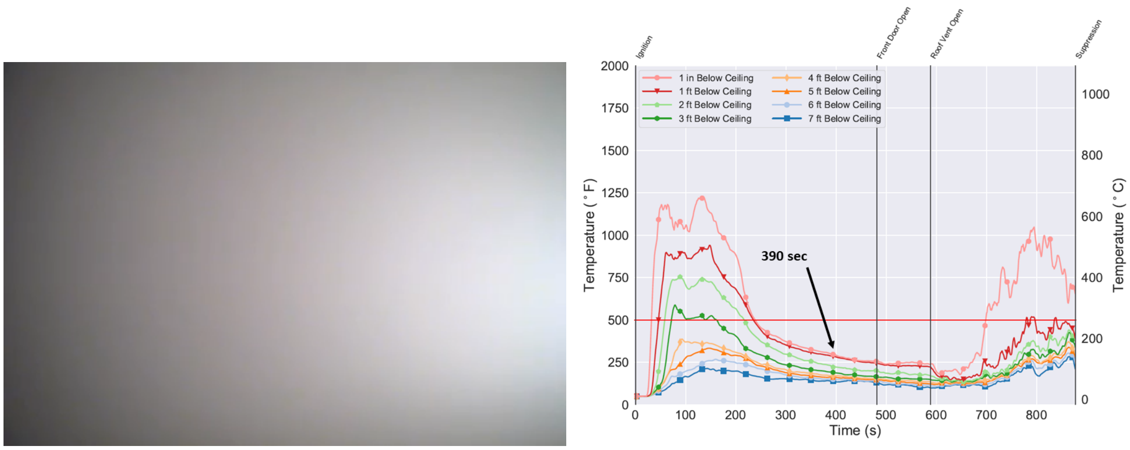


Figure 5.32: Living Room conditions 390 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

Once the front door was opened, an inrush of air was seen in the Living Room camera as the new source of oxygen worked its way to the fire. The increase in visibility is seen in Figure 5.33. Refer to the discussion from the horizontal ventilation tactical consideration on Smoke Tunneling, in Section 5.1.5. When the front door was the only vent open in the structure, a new flow path was established. The front door opened right into the fire room and as such, the flow path was the space in the Living Room between the fuel package and the door. Higher pressure fire gases exhausted out the top of the doorway as fresh air was drawn in near the floor. The burning during the ventilation limited period was also smoldering in the wood-based fuel package and took a period of time after the front door was opened before visual flaming combustion and temperature rise was noted. In this particular experiment, the roof vent was opened shortly after the front door. As the regrowth began, temperatures rose in the Living Room and approached a second peak (Figure 5.34). This was the second growth stage. With the opening of the roof vent, another new flow path was established. There was now a flow path between the fire and the front door (existing) in addition to the area between the fire and the open roof vent. Because the vent was capable of handling the increased fire size, the heat and products of combustion were exhausted up and out. With the vertical vent working as intended, the front door remained all inflow for additional oxygen to support combustion during the second growth phase and subsequent peak (Figure 5.35). The pallets and straw fuel package remained fuel limited throughout the second phase of fire development post ventilation. The second peak was short lived as the fuel mass was consumed quickly. Temperatures in the Living Room began to decline up until the point of suppression (Figure 5.36). The ventilation profile remained the same from the period of time in which the roof vent was opened through suppression and the completion of the experiment. As such, no new flow paths were established.

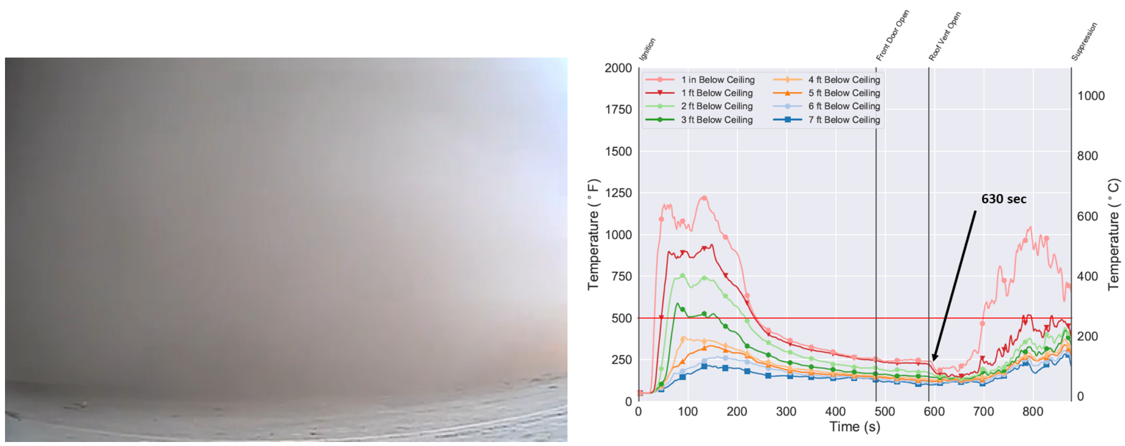


Figure 5.33: Living Room conditions 630 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

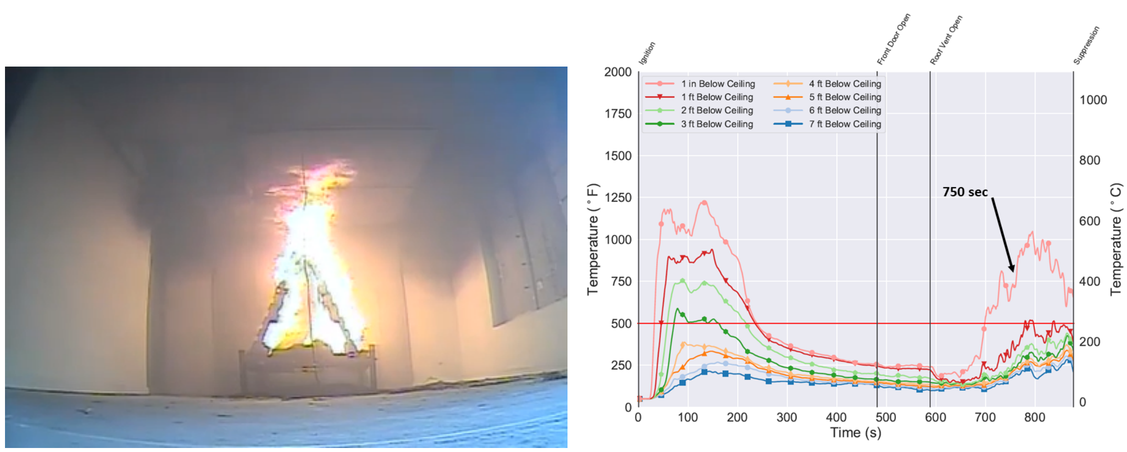


Figure 5.34: Living Room conditions 750 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

The locations of the flow paths in the structure would be the same regardless of the fuel package, either with wood-based training fuels or furniture. The locations of the flow paths would only change if the fire location was changed or the ventilation opening location changed, as in Experiments 7 and 8. The ventilation profile was the same between fuel packages and thus was not a contributing factor to differences in flow paths. With the fire in Bedroom 1, the flow paths would

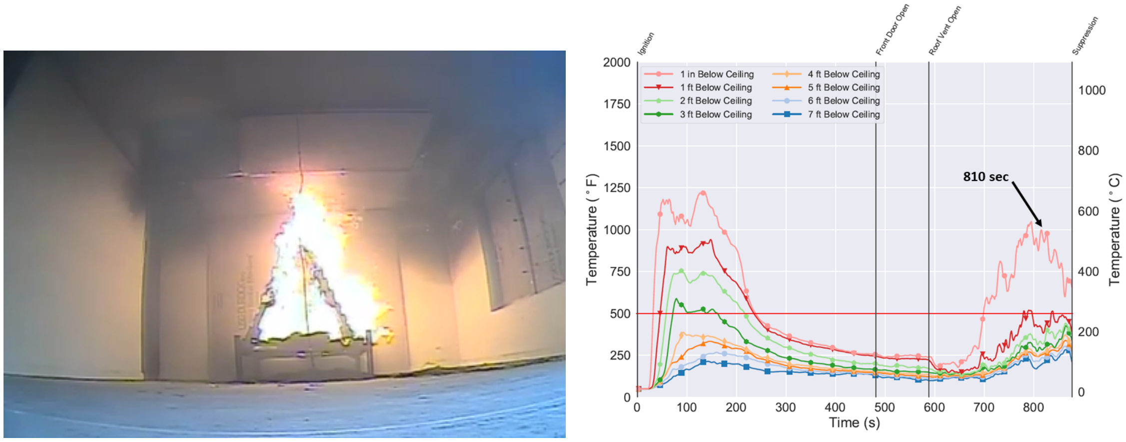


Figure 5.35: Living Room conditions 810 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

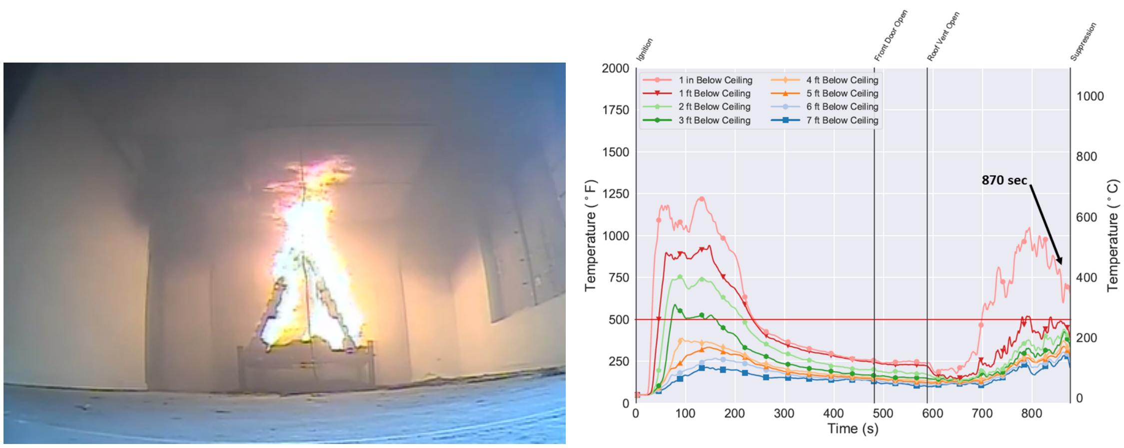


Figure 5.36: Living Room conditions 870 seconds after ignition for Experiment 5: Pallets, Vertical Near Vent. (Left: Video footage; Right: Corresponding temperatures in the Living Room)

now encompass Bedroom 1, the Hallway, and the Living Room. However, the driving factor of fire development (either ventilation or fuel) does change between the fuel packages. With the pallets and OSB and the furniture fuel packages, the fire responds quickly after the front door is opened and before the roof vent is opened. As the fires in these experiments approach a second peak, there is more than enough fuel mass left compared to the ventilation available. This leads to ventilation limited conditions up until the point of suppression which transitions the environment back to fuel limited until complete extinguishment.

While the flow path locations are the same regardless of the fuel package tested, the conditions within the flow path vary. For the furniture experiment, the initial flow path from the fire to the front door remains even after the opening of the roof vent. Whereas with the wood-based training fuels, the front door transitions to an inlet after the roof vent is opened which is a significant difference from what would be seen on the fireground. The wood-based fuel load is small enough and the roof vent is large enough to change the conditions within the existing flow path as all exhaust is then through the vertical vent. This is an important difference that should be highlighted by instructors with regards to how the training ground is different from the fireground.

Teaching the concept of flow paths in structure fires is a key lesson that should be incorporated into all live-fire training evolutions. Operating in the exhaust portion of the fire flow path is a dangerous place to be as firefighters are in the path of travel from where the fire is to where the fire wants to go. Instructors should emphasize that until water is applied directly to the burning surfaces, the fire is likely in a vent limited state, and the conditions in the structure will deteriorate along the flow path. The speed of regrowth and reaction time for firefighters operating in the flow path is dependent on the proximity of the fire to the open vent. Observing conditions in the flow path from a safe location, during live-fire training, is imperative to ensure proper coordination is taking place and that no students or instructors are placed in a position of danger.

5.2.5 Timing is Everything

Fireground Tactical Consideration Summary: *The purpose of venting is to improve the conditions for firefighters to operate. Some of these improved conditions are cooling, increased visibility, and useful flow paths opposite a hose line to release steam expansion. It is not possible to make statements about the effectiveness of ventilation unless one includes timing. Venting does not always lead to cooling; well-timed and coordinated ventilation leads to improved conditions. That same ventilation action 30 seconds earlier or later could have a dramatically different outcome. This is especially true for vertical ventilation. Vertical ventilation is efficient in venting heat and smoke but also causes rapid changes in the conditions in the home. Additional considerations about timing include (i) the fire does not react to additional oxygen instantaneously; (ii) the higher the interior temperatures the faster the fire reacts; (iii) the closer the air is to the fire the faster it reacts; (iv) the higher the ventilation the faster the fire reacts; (v) the more air the faster the fire reacts, the more exhaust the more air that is able to be entrained.* [2]

Coordination on the fireground revolves around the sequencing of fire service interventions in the right place at the right time. Timing of ventilation actions are critical to fireground success for not only victim survivability and firefighter safety but overall incident stabilization as well. Timing needs to be highlighted in training to emphasize its importance. Sometimes tactical discipline is required to wait for the right time to coordinate actions. Just because a firefighting crew is ready to conduct vertical ventilation, doesn't mean that the interior firefighters conducting suppression are ready for the hole to be opened. These principles can and should be incorporated into training as well. The correct timing and sequencing of fire service interventions on both the fireground and training ground lead to successful outcomes. There are several useful considerations with regards to timing on the fireground that will be discussed here for their comparison to live-fire training with wood-based fuel packages.

With regards to vertical ventilation, the coordination is even more vital. When the sequencing is coordinated with water application, vertical ventilation can be the most effective means of clearing out the structure. It is high in the space and more efficiently exhausts heat and products of combustion from the structure, leaving the horizontal vents able to entrain fresh replacement air. Because the vent is located in the ideal location, it also causes the most rapid changes with regards to fire behavior in the structure. In this test structure, the vertical vent was framed out, like a chimney, and prevented fire gases from exhausting into the attic space. On the fireground, or in an acquired structure, this safety measure would not be present. If the vertical ventilation is not timed to be in coordination with suppression, the vent would allow fire gases to enter the attic, and likely extend fire into the space. Attic spaces are ventilated naturally through eves and gable ends, which help to provide air in the space to support combustion. Appropriate timing would ensure that water is on the fire either just before or simultaneous with the opening of the roof vent.

The fire does not react to additional oxygen instantaneously. A ventilation action may appear to be positive at first, as air is entrained into the ventilation-limited fire; however, two minutes later, conditions could become deadly without water application. **[2]** Experiment 5 with a pallets fuel package began with all vents closed. The fire transitioned to a vent limited state before the first fire service intervention was performed. The front door was opened first, which served as the simulation for crew entry but also needs to be thought of as another type of horizontal ventilation as discussed in Section 5.1.2. Once the front door was opened, the fire in the Living Room did not begin regrowth instantaneously even though it was in close proximity to the vent. Temperatures actually remained steady in the Living Room for the duration of time between the front door being opened and the opening of the roof vent. See Figure 5.37.

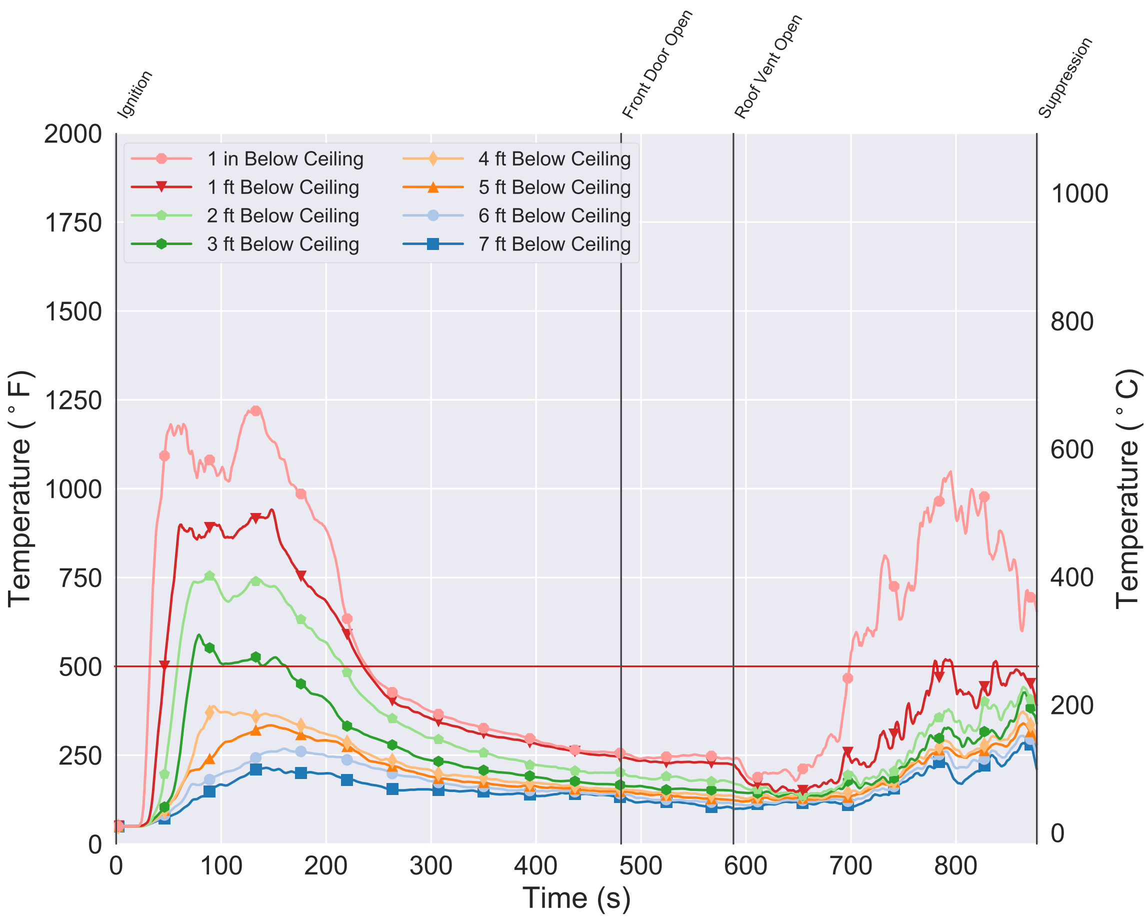


Figure 5.37: Temperatures in the Living Room for Experiment 5 showing delayed response to ventilation.

Additionally, once the roof vent was opened, the temperatures in the Living Room actually dropped for a short period of time as the vent was working as intended. Regrowth began a short period of time later, after both the front door and roof vent were opened. This highlights the fireground consideration that the ventilation does not always have an immediate impact on regrowth. These experiments with wood-based training fuels confirm this concept as the burning is deep-seated in the pallets fuel packages before going ventilation limited prior to intervention. Live-fire evolutions need to incorporate a discussion regarding the difference in timing with regards to responses to ventilation. It was consistent that the pallets and OSB fuel packages responded with temperature rise quicker, and in some cases almost instantaneously with the opening of the vent. Different fuel packages and fire room locations lead to varying responses. Emphasis should be placed on the fact that while a negative response to ventilation may not be seen immediately, it could be coming. A tactical pause may be needed on the training ground or fireground to determine the effectiveness of ventilation before committing crews to the interior.

***The higher the interior temperatures, the faster the fire reacts. If fire is showing on arrival, the interior temperatures are higher than if the house is closed. This means that additional ventilation openings are going to create more burning in a shorter period of time.* [2]** Peak temperatures during the initial growth of a fire can often dictate the time in which the fire reacts to additional ventilation. Throughout the experiments conducted with wood-based training fuels, it was consistent that the pallets and OSB fuel packages reached higher temperatures in the fire room when compared to the fuel packages containing just pallets. The fires reach an initial peak and enter a vent limited state where temperatures begin to decline both in the fire room and throughout the structure. With all vents closed initially, the fires decay much in the same manner regardless of the fuel package. However, because the initial peak temperatures are higher with furniture and pallets and OSB, the temperatures in the fire room at the time in which ventilation occurs are also higher. Higher fire room temperatures in addition to the fire room proximity to the vent are also driving response times. Note in Figure 5.38, at the time of opening the front door.

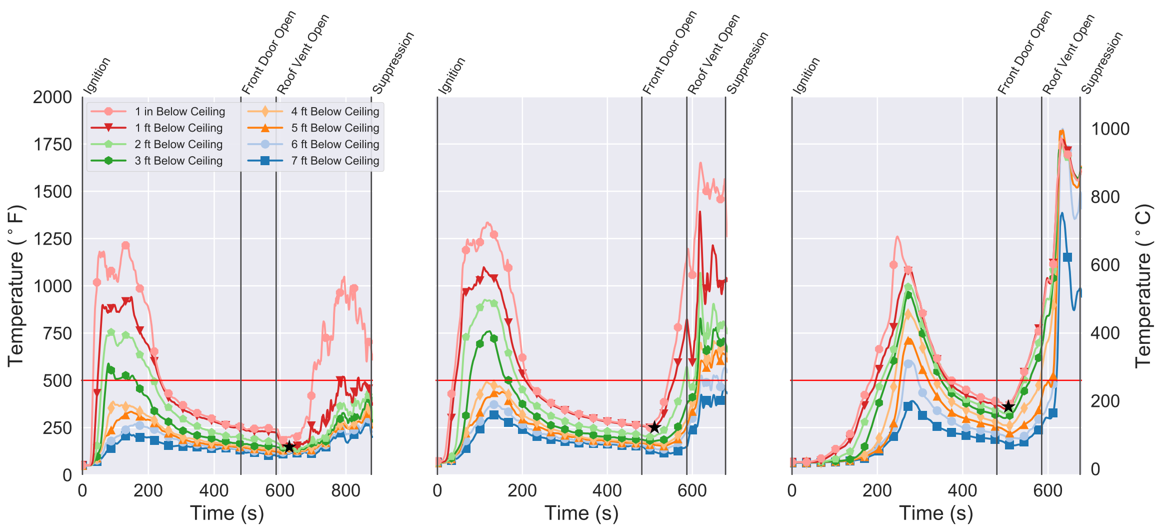


Figure 5.38: Living Room temperatures for the vertical near-vent case. (Left: Test 5 Pallets; Middle: Test 6 Pallets and OSB; Right: Vertical Test 5 Furniture)

During the pallets experiment, temperatures floor to ceiling were less than 250 °F. The pallets and OSB fuel package also had fire room temperatures less than 250 °F at the time of intervention. The experiment with furniture had temperatures at the time of front door open in the range of 250-500 °F. The higher temperatures in the space led to a quick time to temperature rise and beginning of regrowth. Regrowth for pallets began 126 seconds after the front door was opened compared to 27 seconds with pallets and OSB. With higher temperatures at the time of venting, the furniture experiment began regrowth in just 18 seconds after the front door was opened. This was the quickest time for regrowth across the three tested fuel packages. The training ground should incorporate the concept of higher temperatures leading to quicker regrowth times as a means to show the importance of coordination on the fireground. No experiments conducted with wood-based training fuels incorporated fire showing on arrival, but much like the fireground, the concept that fire showing means higher temperatures inside should be emphasized and included in live-fire evolutions when possible.

***The closer the air is to the fire, the faster the fire reacts. Venting the fire room will increase burning faster, but it will also let the hot gases out faster after water is applied.* [2]** From the experiments conducted with furniture, it was found that the closer the vent is to the fire, the faster the fire reacts to the new source of oxygen. For example, venting in the fire room provides quicker regrowth times when compared to venting remote from the fire. This was consistent across all ventilation types: horizontal, vertical, and positive pressure. In the acquired experiments with wood-based training fuels, this principle was also seen specifically regarding the tests with vertical ventilation. The vertical ventilation near vent experiments had the fire located in the Living Room. The front door opened directly into this space, as did the vertical vent. The vertical ventilation far vent experiments had the fire located in Bedroom 1. The front door opened into the Living Room, as did the vertical vent, which placed the seat of the fire farther from the source of oxygen. Figures 5.39 and 5.40 show the Living Room temperatures for these experiments.

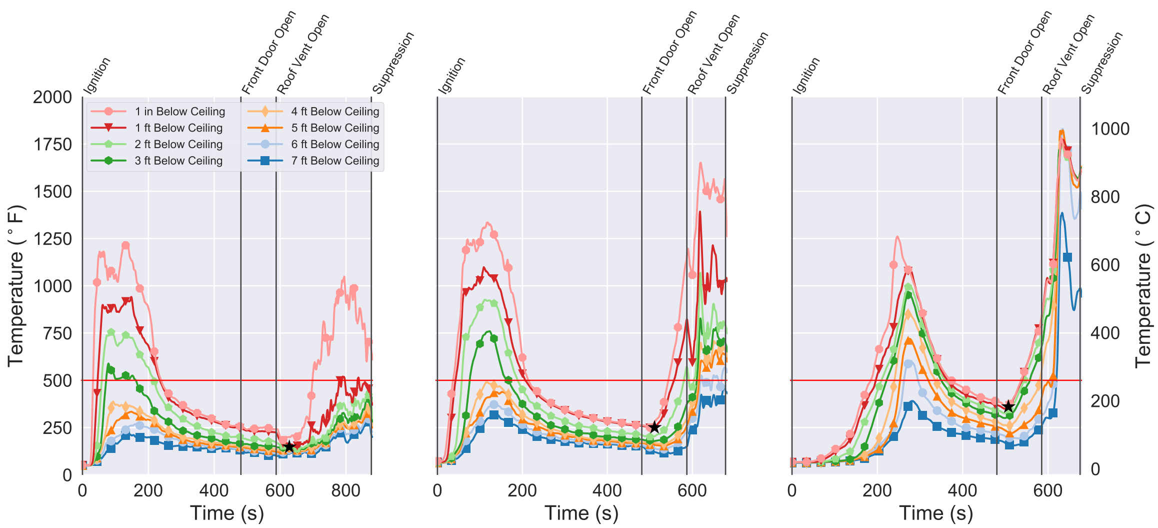


Figure 5.39: Living Room temperatures for the vertical near-vent case. (Left: Test 5 Pallets; Middle: Test 6 Pallets and OSB; Right: Vertical Test 5 Furniture)

If we examine the regrowth start times across the six experiments, we see that the tests with the fuel package in the Living Room respond quicker than those with the fuel package in Bedroom 1. Refer to Table 5.3.

Table 5.3: Timing of Regrowth for Vertical Ventilation Experiments

Experiment	Fuel Package	Vent Location	Regrowth Time
5	Pallets	Near	126 sec
6	Pallets & OSB	Near	27 sec
Vert 5	Furniture	Near	18 sec
7	Pallets	Far	156 sec
8	Pallets & OSB	Far	56 sec
Vert 9	Furniture	Far	151 sec

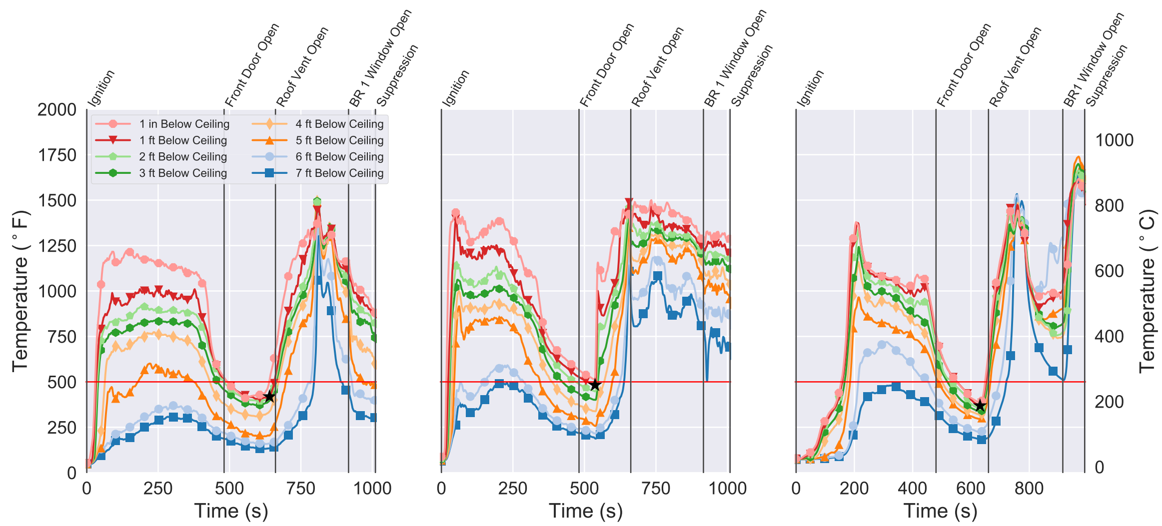


Figure 5.40: Bedroom 1 temperatures for the vertical far-vent case. (Left: Test 7 Pallets; Middle: Test 8 Pallets and OSB; Right: Vertical Test 9 Furniture)

Not only does the increase in fuel mass; pallets to pallets and OSB to furniture, show a decrease in regrowth time, it is also consistent that the fires are slower to respond to ventilation when located in Bedroom 1 compared to the experiments with the fires in the Living Room. In Experiment 8, the pallets and OSB responded quicker than the furniture and could be due to the proximity of the burning fuel to the open vent.

This concept needs to be highlighted on the training ground with regards to ventilation on the fireground. Fireground ventilation needs to be planned and communicated. Indiscriminate ventilation without coordination with water application can be dangerous to crews operating on the interior of the fire building as well as any trapped occupants. The timing is even more vital with the ventilation occurring in the fire room, versus remote which leads to quicker regrowth and less reaction time. Live-fire evolutions need to emphasize the importance of not only the timing of ventilation but also the location. These training evolutions also have the potential to demonstrate that ventilation at any point is effective and require explanation of how this may relate, or not relate, to the fireground.

The higher the ventilation, the faster the fire reacts. Faster and more efficient ventilation means faster air entrainment, which means more burning and higher temperatures. It also means better ventilation after water is applied. **[2]** Previous experiments conducted with furniture show that, in general, the higher the ventilation in the structure, the faster the fire reacts. This is referring to the fact that the vertical vents are allowing heat and products of combustion to exhaust up and out, aided by buoyancy. Vertical vents allow for more of the front door (and any other horizontal vent openings) to serve as more of an inflow and source of fresh air and oxygen for the fire. With wood-based fuels, it was noted that the vertical ventilation openings allowed for the front door to become entirely inflow, as discussed in Section 5.2.3. With furniture, it was shown that the fuel package can overwhelm the vertical vent during regrowth and cause the front door to remain bi-directional flow throughout the test (near vent). To examine the location of the vent in the structure (high versus low), both horizontal and vertical experiments must be analyzed. Table 5.4 shows the regrowth times for the near vent experiments, both horizontal and vertical ventilation.

Table 5.4: Timing of Regrowth for Near Vent Experiments

Experiment	Fuel Package	Regrowth Time
1	Pallets	43 sec
2	Pallets & OSB	29 sec
Horiz 3	Furniture	0 sec
5	Pallets	126 sec
6	Pallets & OSB	27 sec
Vert 5	Furniture	18 sec

Based on the regrowth times from the experiments conducted with wood-based training fuels, the horizontal tests actually show quicker regrowth times compared to the vertical tests. This does not support the conclusion from the previous fireground study. This tactical consideration derived from the furniture experiments used a vertical vent that was 4.0 ft. by 8.0 ft. in addition to a 4.0 ft. by 4.0 ft. vent. In testing only the 4.0 ft. by 4.0 ft. vent for wood-based fuels, the conclusion cannot be drawn that higher ventilation yields quicker regrowth times. This is likely due to only testing the smaller of the two vertical vents which would affect the conclusions when compared to a vertical vent that is twice the size. However, it should be noted that the horizontal window vent in the Living Room was twice the size of the other bedroom windows. The Living Room window was 4,320 square inches compared to the 4.0 ft. by 4.0 ft. roof vent which was 2,304 square inches. This difference in vent size could also be a contributing factor.

The more air, the faster the fire reacts. Also, the more exhaust, the more air that can be entrained into the fire. A bigger ventilation hole in the roof means that more air will be entrained into the fire. If the fire is fuel limited, this is good, but if the fire is ventilation-limited, this could be bad. **[2]** For the purpose of the wood-based training fuels in acquired structures, only one size vertical vent was tested. A fixed 4.0 ft. by 4.0 ft. hole was utilized for all experiments. As such, the ability to compare different size ventilation openings is not possible. As discussed above, if the discussion is broadened to include the horizontal ventilation experiments, the Living Room window was near twice the size of the vertical vent, and did lead to quicker regrowth.

5.2.6 Reading Smoke

Fireground Tactical Consideration Summary: *Looking at smoke conditions is a very important component of size-up, but firefighters should not get complacent if there is nothing showing on arrival. In many of the experiments the smoke color changed from black to grey as the fire became ventilation-limited and the pressure within the house decreased. Ten seconds later there was no visible smoke showing at all. No or little smoke showing could mean a fuel-limited fire that is producing little smoke or it could mean a ventilation-limited fire that is in the initial decay stage and starved for air. In order to increase firefighter safety, consider treating every fire like it is ventilation-limited until proven otherwise.* [2]

As discussed with horizontal ventilation (Section 5.1.3), the ability to read smoke on the fireground is critical to understanding the state of the fire and the effectiveness of various fire service interventions. Reading smoke does not stop with the initial size-up, pre-intervention. On arrival, crews must conduct a 360 degree size-up of the structure, which includes noting the smoke and fire conditions present at that time. Size-up continues as the entry door is forced for firefighter entry. The condition of the smoke (color, density, velocity) should be noted and communicated as needed. Care should be given to noting the location of the neutral plane within the opening and a tactical pause should be given to see if this changes over the course of a couple seconds. Size-up continues throughout the duration of the incident, not only for those in command, but any and all crews operating on the fireground. As various fire service interventions are performed, crews need to evaluate the smoke changes evident. Changes in smoke conditions often indicate whether a given tactic was effective or ineffective. For example, if the roof is ventilated and the status is suppression is unknown. The smoke venting from the hole may become more turbulent and dark before transitioning to flaming combustion. Often times, this is thought of as a sign for effective vertical ventilation, but likely translates to fire extension into the attic space as water may not be on the seat of the fire yet.

Figure 5.41 shows conditions evident from the front side of the structure at various points during Experiment 5, as an example. Experiment 5 incorporated a pallets fuel load, which had the smallest mass and produced the lightest volume and color of smoke. This was chosen as an example to show what the minimum amount of smoke showing was across the experiments conducted.

Figure 5.41: Side A Footage at 4, 7, 9, and 10 minutes after ignition.

The top left of the figure above shows conditions at four minutes after ignition which is during the initial growth phase of the fire before any ventilation occurs. A small amount of light smoke is showing from around the front door and Living Room window. With furniture fuels, this smoke would likely be darker and under more pressure. At seven minutes after ignition (top right), the front door is getting ready to be opened. This is assumed to be the time of fire department arrival in which no smoke is evident from the structure. Arriving to nothing evident from the structure can be grossly misleading to firefighters who are unaware of a ventilation limited fire condition present on the interior with the potential for rapid regrowth upon opening a door or window. The bottom left shows conditions after the door has been opened, but prior to the roof vent being opened. The front door is currently bi-directional flow as the top portion was exhausting heat and products of combustion while the lower portion, closer to the floor, was serving as an inlet. With furniture fuels, the smoke exhausting from the front door would likely be dark and turbulent, possibly under more pressure, and drive the neutral plane lower to the floor. The last image, on the bottom right, shows conditions after the roof vent has been opened. At this point, smoke stops showing from the front door as the roof vent is capable of handling the increased fire size during regrowth. This leaves the front door as a uni-directional inlet. Depending on the size (mass) and orientation of the fuel loading in the compartment, this uni-directional behavior at the door may or may not be present with synthetic furnishings and should be highlighted as a potential difference between the training ground and the fireground.

Hands on training, including live-fire evolutions, often focus on the implementation of various fireground tasks, such as deploying handlines, conducting ventilation, and suppressing the fire. Size-up needs to be incorporated into training, and acquired structure burns are one of the most ideal times to do so. The use of an acquired structure helps the students to visualize the fireground in a much more realistic setting than that of a concrete burn building or metal container prop on the training ground. As seen in the footage from Experiment 5, size-up is ongoing and different principles can be shown at different points during the evolution, beginning with the concept of no smoke showing on arrival. Emphasis of continued size-up of visual cues on not only the training ground but fireground is vital for insight into the effectiveness of tactics.

5.3 Positive Pressure Attack

The tactical considerations produced by the previous project titled *Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices* [3] are listed below. The listed items shaded gray were deemed to be outside the scope of this study and therefore are not considered during the comparison of experimental results to the tactical considerations. As discussed in Section 1.2, the number of experiments allotted for positive pressure attack limited the scope and amount of variables able to be tested. Positive pressure attack and positive pressure ventilation have often been used interchangeably. However, for the purpose of this report, positive pressure attack is defined as fan usage before and during fire control. Positive pressure ventilation is defined as fan usage post fire control. This study did not focus on suppression or any activity after fire control, thus tactical considerations regarding fire attack and positive pressure ventilation post fire control are not discussed. Additionally, there was not a closed door component to this test, and as such, this is not discussed as a comparison.

Experiments 9 — 12 with wood-based fuels in acquired structures examined positive pressure ventilation. Experiments 4 and 6 from the fireground positive pressure ventilation research [3] conducted previously are utilized as comparisons with similar vent profile and fire location.

Table 5.5: Positive Pressure Attack Study Tactical Considerations

Tactical Consideration Title	Section
Horizontal, Vertical, and Positive Pressure Attack are Different Tactics	5.3.1
The Setback of the Fan or the Development of a Cone of Air is not as Important as the Exhaust Size	N/A
During PPA, an Ongoing Assessment of Inlet and Exhaust Flow is Imperative to Understanding whether or not a Fan Flow Path has been Established and if Conditions are Improving	5.3.2
Positive Pressure Attack is Exhaust Dependent	5.3.3
An Outlet of Sufficient Size Must Be Present in the Fire Room to Allow for Effective Positive Pressure Attack	5.3.4
During a Positive Pressure Attack, Creating Additional Openings Not in the Fire Room will create Additional Flow Paths Making Positive Pressure Attack Ineffective with the Potential to Draw Fire into All Flow Paths	5.3.5
The Safety of Positive Pressure Attack is Decreased when the Location and Extent of the Fire is Not Known with a High Degree of Certainty	N/A
Positive Pressure Attack will not be Effective on a Fire Located in an Open Concept Floor Plan or any Floor Plan with High Ceilings	N/A
The Application of Water, as Quickly as Possible, From Either the Interior or Exterior prior to Initiating a Positive Pressure Attack will Increase the Likelihood of a Successful Outcome	N/A
Positive Pressure Attack is not a Replacement for Using the Reach of Your Hose Stream	N/A
During a Positive Pressure Attack, Extension into Void Spaces is Directly Related to the Exhaust Capabilities of the Void Space	N/A
Positive Pressure Attack Does Not Negatively Affect the Survivability of Occupants Behind a Closed Door	N/A
When Positive Pressure Ventilation is Utilized Post Fire Control, in Single Story Residential Structures, the More Openings Made in the Structure During Positive Pressure Ventilation, The More Effective it is at Ventilating the Structure	N/A
When Positive Pressure Ventilation is Used Post Fire Control, it is Important to Assess for Extension	N/A
When Positive Pressure Ventilation is Used Post Fire Control, Starting or Turning in the Fan Immediately After Fire Control will Provide the Most Benefit	N/A

5.3.1 Horizontal, Vertical, and Positive Pressure Attack are Different Tactics

Fireground Tactical Consideration Summary: *No one tactic will work in every scenario. Understanding the fire environment with emphasis on ventilation-limited fire dynamics and how fire department operations impact those will ensure the tactic chosen is most effective.* [3]

The experiments described in this report revealed that employing different ventilation techniques during fires with wood-based training fuel loads can have varying effects on thermal conditions throughout a structure. This trend was also prevalent amongst comparisons of thermal data from experiments conducted for previous projects focused on horizontal ventilation, vertical ventilation, and positive pressure attack; all of which utilized furniture fuel packages.

An example of differing effects between the considered ventilation tactics is provided by the graphs in Figure 5.42, which contain the Bedroom 2 temperature data plotted over the duration of the far vent experiments with horizontal ventilation and positive pressure attack for each fuel package. During these scenarios, the fuel package was located in the Living Room. Horizontal ventilation was employed via the front door and rear window of Bedroom 2 after the fire transitioned to a decayed, ventilation-limited state. Then, during the positive pressure attack tests, a fan positioned outside the front door was turned on to initiate PPA.

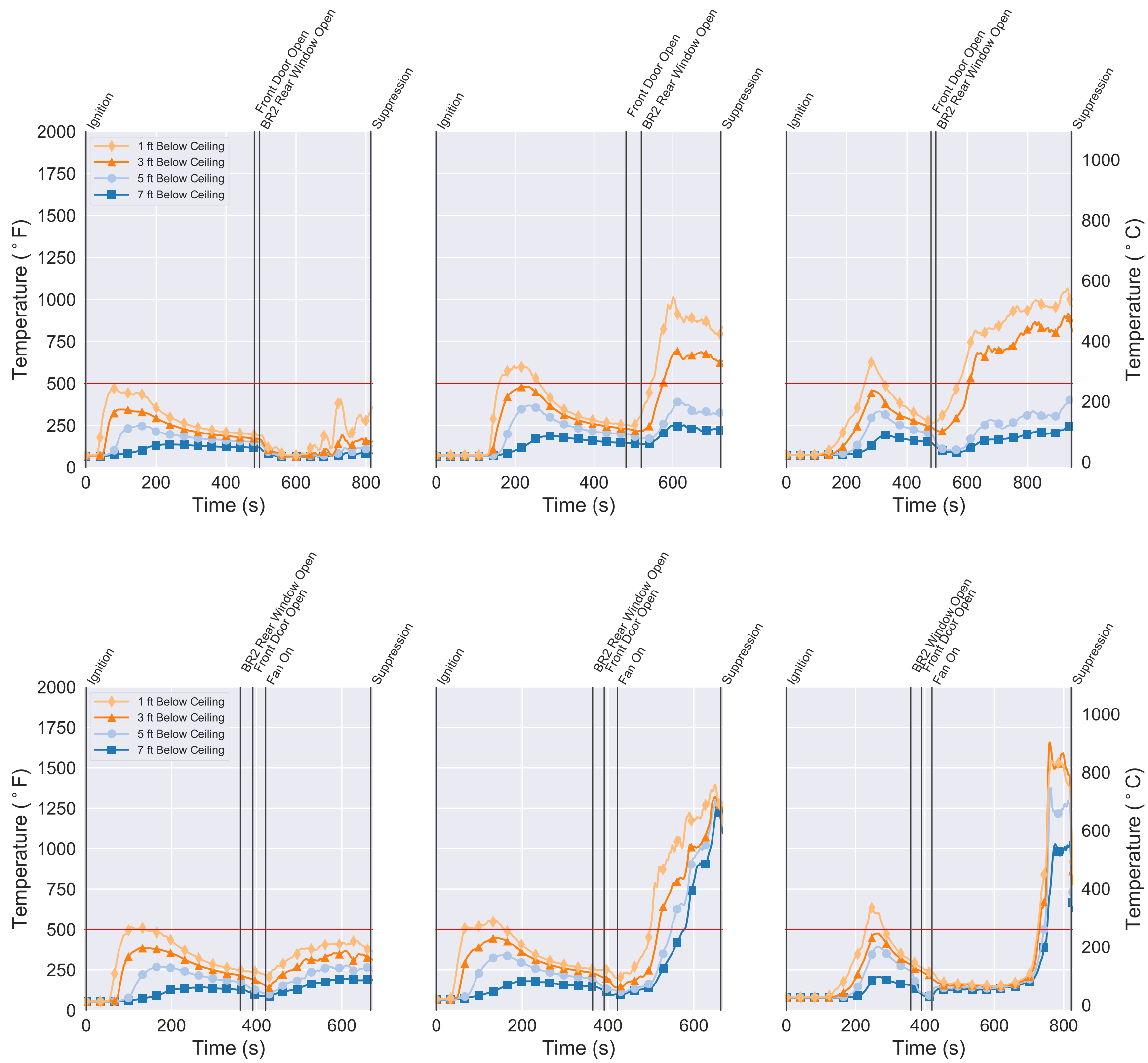


Figure 5.42: Bedroom 2 temperatures from horizontal ventilation (top) and positive pressure attack (bottom) far vent experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

Both horizontal ventilation and positive pressure attack measures caused the fire to regrow from its ventilation-controlled state to a more developed state for the new vent profile. However, as shown by the plots in Figure 5.42, there was a noticeable difference in the rate of temperature rise after the start of regrowth between the two ventilation tactics. Upon the start of regrowth, conditions deteriorated at a quicker rate during the experiments with PPA (bottom graphs) compared to the horizontal ventilation experiments (top graphs).

Additionally, the impact of vertical ventilation on the thermal environment differed from that of other ventilation types. Comparing results between the near vent experiments with horizontal ventilation and vertical ventilation for each fuel load illustrates some of these dissimilarities. Both test procedures involved igniting the fuel package in the Living Room and opening the front door eight minutes later. Shortly after the front door was opened, the Living Room window was opened in the horizontal ventilation case, and a 4.0 ft (1.2 m) by 4.0 ft (1.2 m) vent was opened above the Living Room during the vertical ventilation experiments. Examination of the front door bi-directional probe data from these experiments with each fuel load, which are plotted in Figure 5.43, reveals that horizontal and vertical ventilation had different effects on conditions at the front door.

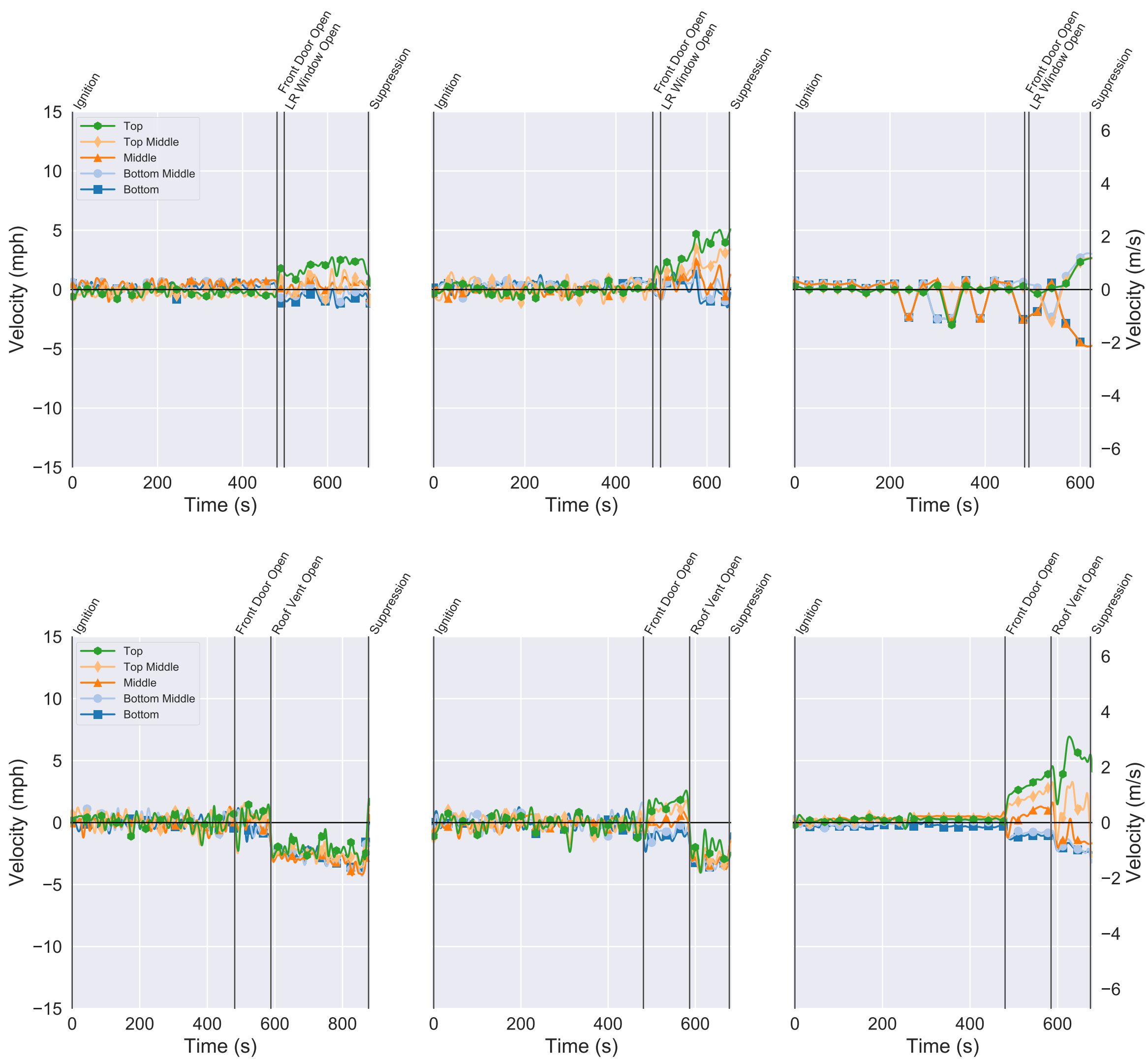


Figure 5.43: Gas velocity measurements collected at the front door during the horizontal ventilation (top) and vertical ventilation (bottom) near vent experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

Looking at Figure 5.43, after vertical ventilation was performed during the experiments with wood-based fuel loads, flow through the door opening immediately transitioned from a bidirectional state to a unidirectional state with all gases flowing into the structure. Alternatively, bidirectional flow through the door opening continued after the vertical vent during the fire with the furniture fuel load. In fact, the exhaust gases at the doorway continue to increase. Discrepancies like this regarding response to ventilation between fires with *NFPA 1403*-compliant fuel loads and those primarily composed of synthetic materials and foam plastics need to be properly understood by instructors and transmitted to students during training. Otherwise, students may form incorrect impressions based on their experiences during fire training, such as "venting always improves conditions," which could lead to detrimental decisions on the fireground.

As was discovered by comparing results between previous experiments that utilized furniture fuel packages, incorporating different types of ventilation during training fires with wood-based fuel loads can result in a variety of outcomes. However, the variation in outcomes between different ventilation tactics may not be the same during training fires as during fires with fuels primarily composed of synthetic materials and foam plastics. The results from the experiments conducted for this report and other portions of the project titled *Study of the Fire Service Training Environment: Safety, Fidelity, and Exposure* are aimed at better understanding this gap between the live-fire training experience and the fireground. Using the results from this project on wood-based fuels combined with the knowledge gained from previous projects focused on furniture fuels, instructors responsible for live-fire training should be able to effectively prepare evolutions utilizing different ventilation techniques with known outcomes to provide students with a safe yet realistic representation of the fireground.

5.3.2 During PPA, an Ongoing Assessment of Inlet and Exhaust Flow is Imperative to Understanding whether or not a Fan Flow Path has been Established and if Conditions are Improving

Fireground Tactical Consideration Summary: *The fire attack entrance cannot tell you the conditions at the exhaust location(s). Assessing both the inlet, exhaust locations and interior conditions together provide the best assessment of PPA effectiveness.* [3]

During the experiments with furniture fuel loads conducted for the previous fireground project, "back flow" — the exhausting of fire gases from the structure — was always observed at the inlet while the fan was turned on, regardless of the size or location of the opening. This finding indicates that unidirectional inflow may not occur at the inlet opening during positive pressure attack. During the far vent PPA experiment with the pallets fuel load, unidirectional inflow was present at the front door while the fan was on. However, when OSB was added to the pallets fuel load, the increased fire size caused back flow to occur at the front door during the fan operation. This phenomenon can be seen in the front door bi-directional probe data from these experiments, which are plotted in Figure 5.44.

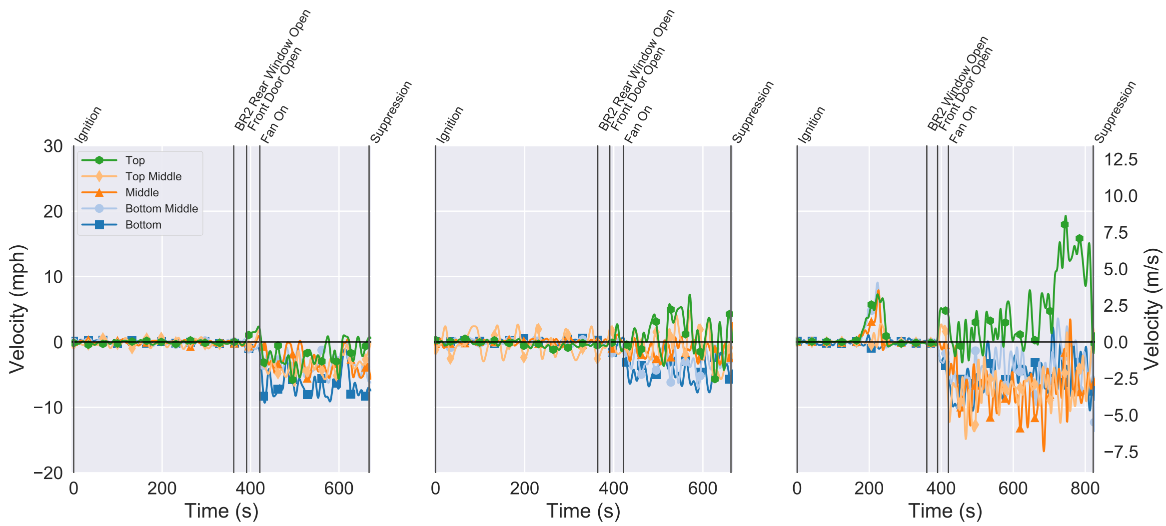


Figure 5.44: Gas velocity measurements collected at the front door during the far vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

Notice how after fan is turned on during the experiment with the pallets fuel package, each BDP measurement location transitions to negative values, indicating unidirectional flow *into* the structure. However, after the same event during the experiments with the pallets and OSB and furniture fuel packages, the top BDP measured positive velocities, indicating there was flow *out of* the structure near the top of the doorway even while the fan was running. Additionally, as shown by the still frames of experimental video recordings that appear in Figure 5.45, there was visible exhaust smoke near the top of the doorway 60 seconds after PPA was initiated during these two experiments, whereas there was no visible smoke at the doorway during this period of the experiment conducted with the pallets fuel package.

Figure 5.45: Images of the front door 60 seconds after the fan was turned on during the far vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel loads.

The fact that there was always some back flow at the fan inlet during the experiments with furniture fuel packages implies that a visual assessment of conditions at the inlet is not sufficient for determining the effectiveness of positive pressure attack — conditions at the exhaust vent(s) should also be examined when determining the effectiveness of positive pressure attack.

As stated in the report regarding the PPA experiments with furniture fuel loads, given a scenario where PPA is initiated at the front door of a structure with an exhaust at a window opening, "Once the fan is turned on, the neutral plane should drop to the window sill, and the exhaust should become a unidirectional flow indicating the fan flow path has been established." [3] Such behavior was observed not only during the far vent PPA experiments with furniture fuels but also during those with the wood-based fuel packages that are described in this report. During these experiments, the fuel package was located in the Living Room, the inlet was the front door, and the exhaust was the Bedroom 2 rear window opening. Plots of the BDP data collected at the Bedroom 2 rear window opening during the three experiments are presented in Figure 5.46. All data after the fan was turned on are positive, indicating the window opening became a unidirectional exhaust vent immediately following the event. Furthermore, the still frames of the experimental video recordings that appear in Figure 5.47 show the smoke conditions before and after the transition to unidirectional flow through the window opening caused by positive pressure attack.

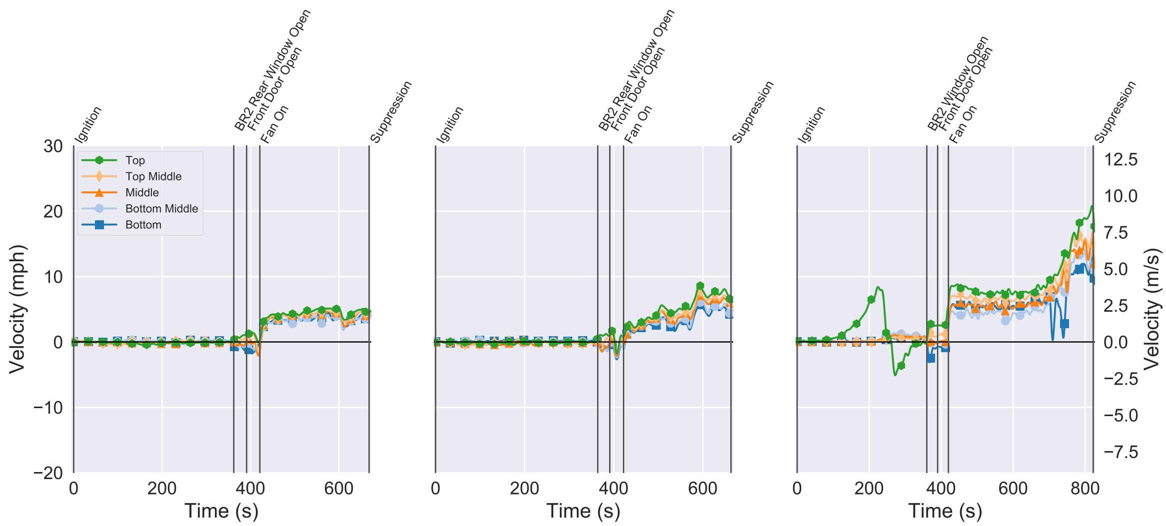


Figure 5.46: Gas velocity measurements collected at the Bedroom 2 rear window during the far vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

Figure 5.47: Images of the Bedroom 2 rear window five seconds before (top) and 30 seconds after (bottom) the fan was turned on during the far vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel loads.

The results indicate that conditions produced by fires with wood-based fuels can also exhibit the need to continually assess conditions at the inlet and exhaust openings during PPA to determine if a flow path has been established by the fan and if conditions are improving. This coincides with furniture fires seen on the fireground. However, it should not be assumed that such conditions can always be generated by training fires with wood-based fuels. The experiments described in this report are limited in their scope and do not encompass all possible outcomes of utilizing PPA during fire training. Amongst other limitations, the experiments were performed in a single building that was intended to represent an acquired structure and only considered two training fuel load configurations. The design of the training structure, configuration of the fuel packages, size of the fuel package, ventilation profile, timing of specific interventions, and a number of other factors can dictate whether certain aspects of fire response to PPA can be replicated on the training ground. Instructors should conduct multiple evolutions prior to student involvement to determine the proper balance of these factors that produces desired outcomes during training with PPA and keeps the thermal hazard at an appropriate level based on the ability and experience of the students.

5.3.3 Positive Pressure Attack is Exhaust Dependent

Fireground Tactical Consideration Summary: *For PPA to be effective, the pressure created by the fan must be greater than the pressure created by the fire. Although fan size does play a role in the effectiveness of PPA, exhaust size plays a greater role. Providing enough exhaust to reduce the pressure in the fire room below what the fan is capable of producing in the remainder of the structure is essential for safe PPA operations.* [3]

The concept of pressure generation by the fan being greater than that of the fire was also evident during the near vent PPA experiments with wood-based fuels, most notably those that utilized the pallets and OSB fuel packages. The experiments followed a procedure that involved implementing positive pressure attack on a fire located in Bedroom 2 with the front door as the inlet and Bedroom 2 rear window as the exhaust. Approximately one minute and 50 seconds after the fan was turned on, the second window in Bedroom 2 (on the side of the structure) was opened.

The introduction of a second ventilation opening reduced the pressure in the fire room regardless of the fuel load. This reduction of pressure caused the flow of gases through the Bedroom 2 rear window opening to slow, as shown by the rear window BDP data plotted in Figure 5.48. In each chart, the measured velocities decline immediately following the "BR2 Side Window Open" event.

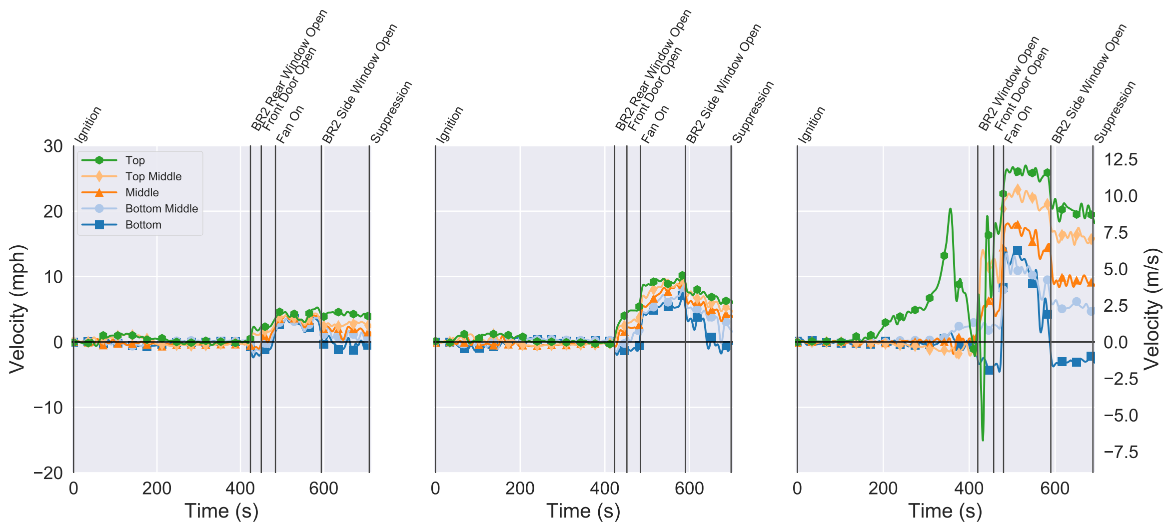


Figure 5.48: Gas velocity measurements collected at the Bedroom 2 rear window during the near vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

According to the fireground report regarding the PPA experiments with furniture fuel loads, the reduction in pressure caused by the additional ventilation opening should improve the effectiveness of PPA: "The greater the differential pressure between the fire room and adjacent spaces, the more effective the PPA will be at keeping fire gases out of the adjacent spaces." [3] This anticipated increase in PPA efficiency was evident in temperature data measured within spaces adjacent from the fire room during the near vent PPA experiments that utilized the pallets and OSB and furniture fuel packages, as shown by the plots of Hallway temperature data from the near vent PPA experiments displayed in Figure 5.49.

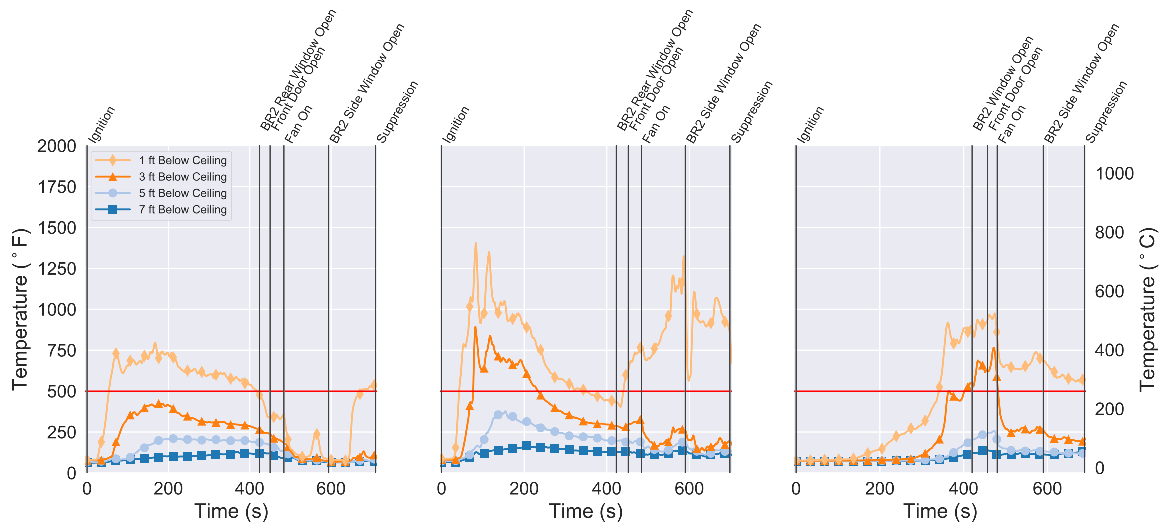


Figure 5.49: Temperatures measured in the hallway during the near vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

Although there was a noticeable decrease in pressure after the second window in Bedroom 2 was opened during the near vent PPA experiment with the pallets fuel load (see Figure 5.48), an increase in PPA efficiency in the form of a decrease in severity of conditions was not apparent in the Hallway. This is because one exhaust opening was already sufficient for the size of the wood-based training fuel load and temperatures were already close to ambient in the space. However, it should be noted that the temperature at the ceiling level in the Hallway began to increase shortly after the second window in Bedroom 2 was opened. The temperature at the ceiling increased to above 500 °F, which was higher than the temperature when just one window was open in Bedroom 2. The temperatures in the lower portion of the Hallway continued to remain at ambient. This was not consistent with either the pallets and OSB or furniture fuel packages which showed a further decrease in temperatures following the second window being opened in Bedroom 2. This could be due to a number of factors including a potential wind gust or issue with the fan operation and cone development during that specific time of the test allowing some fire gases to escape back out of Bedroom 2 at the ceiling level.

Included in the report regarding the PPA experiments with furniture fuel loads is content about the area ratio of the exhaust opening to the inlet opening. The report states, "The most effective way to ensure that the pressure from the PPA in the adjacent compartments is higher than the pressure in the fire room is to have the exhaust openings in the fire room be larger than the inlet opening to the fire room." [3] The door opening into Bedroom 2 was 30.0 in. by 80.0 in. which was 2400 in.^{2} compared to the window openings in Bedroom 2 which were 36.0 in. by 60.0 in., or 2,160 in.^{2}, each. With only one window in Bedroom 2 open, the door opening (or inlet) was larger than that of the exhaust; however, the fire size of the wood-based fuel package involving only pallets was small enough to still have PPA remain effective. With the additional fuel mass in the form of OSB added to the fuel package, consistency was seen when compared to the furniture experiments in that the second window opening allowed a lower pressure in the fire room and thus, a more effective means of positive pressure attack.

Instructors should be intimately familiar with their training structure, whether it be acquired or a fixed on-site facility. Knowing the opening sizes and locations of vents in the structure can allow instructors to design live-fire evolutions emphasizing the concept that PPA effectiveness is exhaust dependent. Live-fire evolutions with differing ventilation profiles can highlight the impact that different size inlet and exhaust openings can have on the effectiveness of ventilating a structure with positive pressure.

5.3.4 An Outlet of Sufficient Size Must Be Present in the Fire Room to Allow for Effective Positive Pressure Attack

Fireground Tactical Consideration Summary: *PPA effectiveness is directly dependent on the ability of the fan to exhaust products of combustion to the exterior. Any exhaust opening created in conjunction with PPA should be located in the fire compartment.* [3]

This fireground tactical consideration highlights the importance of having the exhaust openings in the fire room versus in an adjacent space or remote location. The use of positive pressure has the ability to create unintended flow paths, resulting in the spread of smoke and fire along this path to the exhaust opening. Two tests utilizing wood-based training fuels were conducted as a part of this series which looked at a fire in Bedroom 2 of the structure. The ventilation profile consisted of the rear window in Bedroom 2 being opened followed by the front door and fan operation before a second window in Bedroom 2 was also opened. The exhaust openings for these experiments were in the fire compartment. Temperatures in adjacent and remote locations including the Living Room and Bedroom 1 in the structure are seen in Figures 5.50 and 5.51.

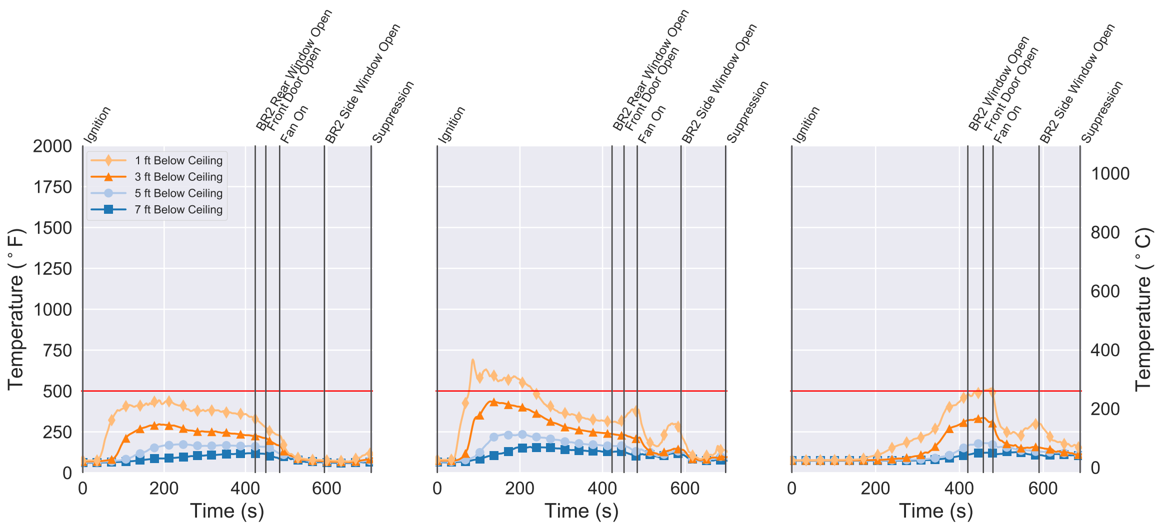


Figure 5.50: Temperatures measured in the Living Room during the near vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

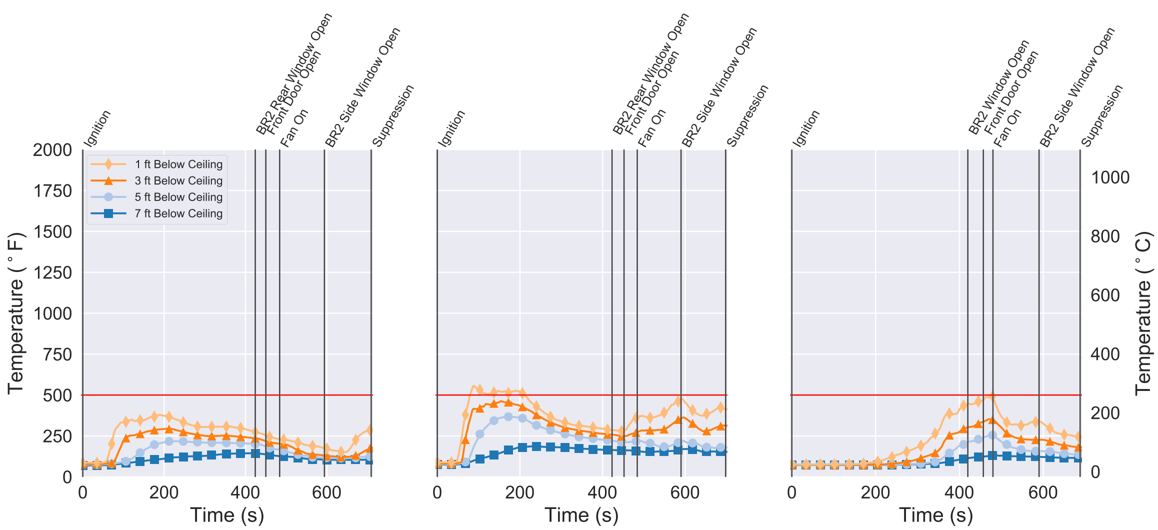


Figure 5.51: Temperatures measured in Bedroom 1 during the near vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

With the fire and exhaust openings located in the same compartment in Bedroom 2 of the structure, the fan is effective at keeping temperatures low in the adjacent and remote spaces. Figure 5.50 shows Living Room temperatures that remain decreasing with the initialization of positive pressure attack via the fan positioned at the front door. These temperatures remain lower than the initial peak, pre-fan, for the duration of the experiment, regardless of the fuel package; both wood-based and furniture. Figure 5.51 shows temperatures in Bedroom 1 which is immediately adjacent to the fire room (Bedroom 2) and just outside of the flow path from the front door to the fire compartment. As with the Living Room, temperatures after the fan is turned on continue to decrease and remain low with the pallets only and furniture fuel package. With the addition of OSB, the temperatures climb slightly but not greater than the initial peak, pre-fan. Each of these experiment confirm that the exhaust opening should be located in the fire compartment for maximum effectiveness and to limit the thermal hazards in adjacent and remote spaces in the structure.

An additional topic mentioned in this tactical consideration is the potential of fire extension to exposures: "As with any ventilation tactic, extension to exposures needs to be a consideration when utilizing PPA. The use of the fan intensifies the volume of fire venting from the exhaust window." [3] Based on the results from the near vent PPA experiments described in this report, those conducting live-fire training should be cognizant of the potential for fire extension to exposures, especially when PPA tactics are involved. For example, consider the still frames from video recordings of the near vent experiments with the different fuel loads that appear in Figure 5.52. Initiating PPA during the experiment with the pallets and OSB fuel load resulted in a volume of fire venting from the exhaust opening that was comparable to the amount observed during the experiment with the furniture-based fuel package. The flames exhausting from the fire compartment will increase in volume and velocity when driven by the fan flow. This should be shown to students as an example of either fan driven or wind driven fire flow with examples of the hazards associated with such a phenomenon.

Figure 5.52: Images of the Bedroom 2 rear window five seconds before (top) and 30 seconds after (bottom) the fan was turned on during the near vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel loads.

5.3.5 During a Positive Pressure Attack, Creating Additional Openings Not in the Fire Room will Create Additional Flow Paths Making Positive Pressure Attack Ineffective with the Potential to Draw Fire into All Flow Paths

Fireground Tactical Consideration Summary: *Additional openings not in the fire compartment will lower the pressure in the adjacent compartments, allowing for more flow from the fire compartment to the remainder of the structure.* [3]

As discussed in Section 5.3.5, keeping the exhaust openings to the fire compartment is critical in ensuring the effectiveness of positive pressure attack. Similarly, if the exhaust opening is located remote from the fire compartment, conditions will likely deteriorate along the newly developed flow path from the fire to the remote vent location. Two experiments were conducted here with wood-based training fuels examining this concept. The far vent PPA experimental procedure included performing PPA on a fire located in the Living Room with the front door as the inlet and Bedroom 2 rear window as the exhaust. Similar to that seen during the experiment with the furniture fuel package, flames and fire gases flowing into compartments adjacent from the fire room was observed during the far vent PPA experiment with the pallets and OSB fuel load. When the pallets fuel load was utilized, no visible flames flow to other areas was witnessed. This is due to the smaller fuel mass and resulting smaller fire size. However, during all three experiments, PPA caused the temperatures in spaces remote from the fire room to increase, as seen in the Bedroom 2 temperatures presented in Figure 5.53.

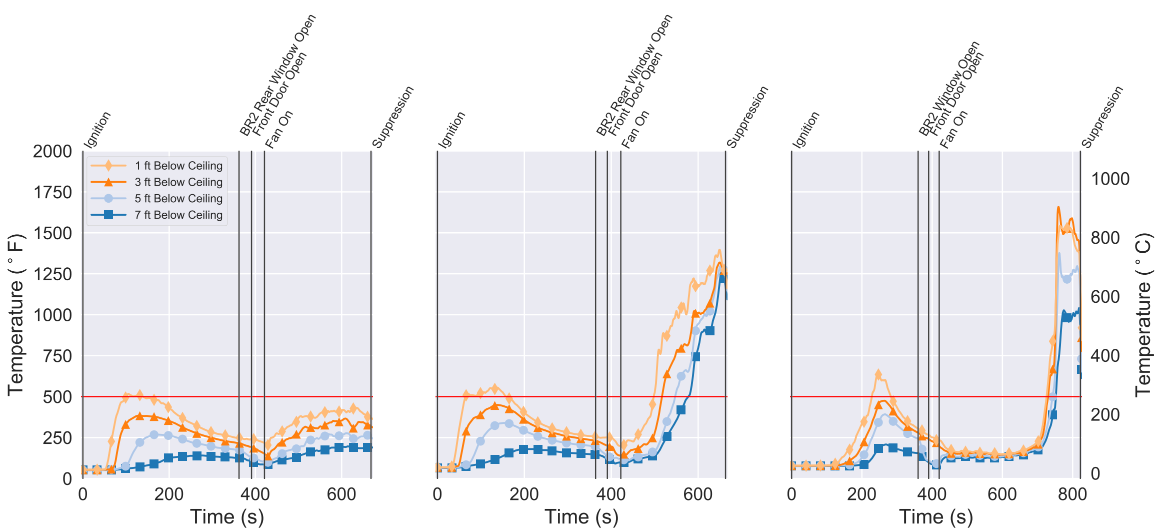


Figure 5.53: Temperatures measured in Bedroom 2 during the far vent PPA experiments with the pallets (left); pallets and OSB (middle); and furniture (right) fuel packages.

After the fan was turned on, the temperatures in Bedroom 2 experienced an increase throughout the space; near to the floor as well as near to the ceiling. This occurred regardless of the fuel package tested, either wood-based training fuels or furniture. In the pallets only experiment, the temperature increase was minimal due to the small fire size. With the additional fuel mass in the form of OSB, the fire size was substantially larger, and thus, experienced a drastically larger increase in temperatures that closer resembled the furniture experiment. Temperatures in Bedroom 2 during these two experiments climbed to above 1000 °F after the fan was turned on.

Additionally, a still frame from the experimental video recording of the experiment with the pallets and OSB fuel package is displayed in Figure 5.54 to show fire extension down the hallway caused by the positive pressure attack.

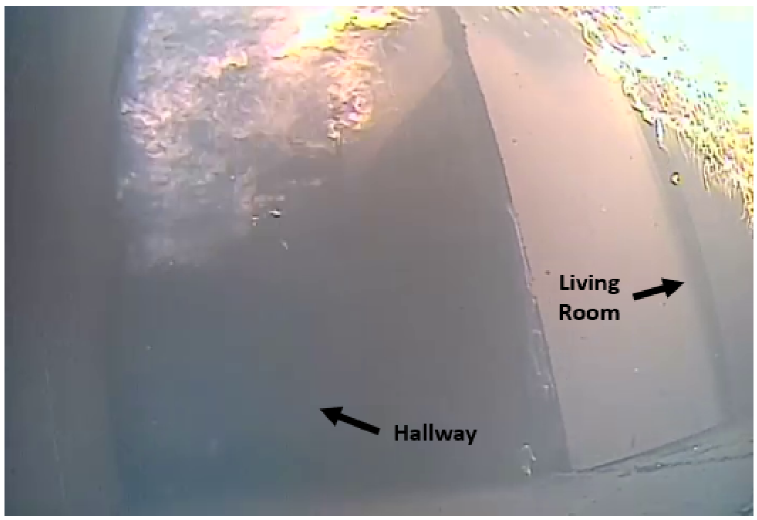


Figure 5.54: Video frame from hallway camera showing flames traveling down the hall towards the Bedroom 2 approximately 90 seconds after the fan was turned on during the far vent PPA experiment with the pallets and OSB fuel package.

Instructors should be cognizant of the location of students in the training structure anytime PPA tactics are being employed. Anyone located in the path between the fire and the exhaust has the potential to be exposed to a thermal threat that would be considered untenable with regards to PPE testing limits.

6 Summary

The balance of fidelity with safety on the training ground continues to be a struggle for fire service instructors as the fire environment is ever evolving with changing materials and furnishings, differing construction practices, and changing requirements put forth by the NFPA 1403 standard on live-fire training. The training ground is often the first place that students are exposed to what conditions they may face on the fireground and as such, is of utmost importance. When faced with a problem, firefighters resort back to their training and the messages that have been ingrained over the course of their career. It is critical that the concepts they internalize on the training ground are representative of what they may face in the field. When seconds count, decisions have the potential to be life or death. Recognition prime decision making is the ability to rapidly identify a problem, determine a method to mitigate the issue, and institute this method based on previous experience. This previous experience is developed beginning on the training ground. Unfortunately, the fire environment will never be static and thus training will constantly change to adapt to the changing conditions seen in the field. Studying both the fireground and the training environment can help bridge the gap between the two and determine what things should be considered when designing live-fire evolutions to maximize fidelity and minimize risk.

In an attempt to further understand the training environment, UL FSRI conducted 12 experiments utilizing wood-based training fuels in a structure similar to that used in previous research studies on fireground ventilation. The fuel locations, intervention timing, and ventilation profiles were identical between these experiments with wood-based fuels and the previous experiments with furniture. With these consistent variables, comparisons were made between the training ground and the fireground to determine if the tactical considerations that came about as a result of the experiments with furniture were able to be replicated with wood-based fuels. The intent of the study was to evaluate live-fire training and highlight potential limitations and considerations for instructors. Two wood-based fuel packages were utilized, one with pallets and the second with pallets and OSB. Horizontal ventilation, vertical ventilation, and positive pressure attack tactics were examined across both fuel loads with two different vent profiles: venting near/above and venting far/remote.

These experiments in acquired structures with wood-based fuels were compared to results from the following UL FSRI fireground projects: *Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction* [1] and *Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes* [2] and *Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices* [3].

Horizontal Ventilation Wood-based fuels showed a similar growth curve to furniture experiments with the same vent profile which highlights the ability to reproduce ventilation limited fire conditions in an acquired structure with allowed training fuels. Reproducing vent limited fire conditions also allows for the training to incorporate responses to ventilation which are more representative of the fireground in terms of regrowth. The front or entry door to the training structure should be considered in the same way as any other horizontal ventilation opening, which provides a new source of oxygen for the fire. Allowing the fire to go ventilation limited during a training evolution can also demonstrate the concept of no smoke showing on arrival as the pressure inside the structure is no longer higher than the pressure outside the structure during this initial decay. Once a horizontal ventilation opening is made, conditions in the structure will deteriorate as regrowth of the fire occurs regardless of the fuel package utilized which emphasizes the need for coordination with fire attack and other fireground actions such as search and rescue. The more fuel mass, the larger the fire pre-ventilation, and the quicker the regrowth post-ventilation. This highlights the potential for decreased response time for firefighters after a vent is made until water is applied to the seat of the fire. Other considerations such as size-up cues for ventilation limited fire conditions and the importance of isolation with vent-enter-search operations were also confirmed with wood-based fuels in acquired structures. Visualization of the flow paths present in the structure was possible with all fuels tested and can be used for instruction to students even though the conditions were drastically different between fuels in some cases.

Vertical Ventilation Similar growth curves between wood-based training fuels and furniture were also seen in the vertical ventilation comparison experiments. Ventilation limited conditions were reproduced in the simulated training environment. The results from wood-based fuels confirmed the need for coordination with water application in order to minimize regrowth once a vent opening has been made, whether that be the front door or a vertical opening in the roof. The location of the vertical vent in the structure, either over the fire or remote from the fire, showed that the more important factor was the potential for a doorway to the fire compartment to serve as a point of restriction in both fire growth and exhaust capability. The presence of a single doorway to a fire compartment produced results that were similar between venting above and venting remote. Without the presence of this doorway, regrowth would be more substantial and would cause worsening conditions along the path from the fire compartment to the vertical vent, regardless of the fuel package. Venting above with coordination of water application would be ideal. Additionally, as the vent profile changes and causes the development of new flow paths, the conditions seen at each respective vent may change depending on the fuel package. For example, with wood-based fuels, the vertical vent was capable of handling the exhausting fire gases and allowed the front door to become unidirectional inflow. This was a discrepancy seen between wood-based fuels when compared to furniture. Timing was discussed to show that the fire may not react to a vent instantaneously, highlighting that while conditions may appear to improve first, this could be temporary before regrowth. The proximity of the fire to the vent opening with regards to regrowth timing showed that the near vent cases experienced quicker response to ventilation than the far vent cases. This also occurred across both wood-based and furniture fuel packages.

Positive Pressure Attack Experimental results with wood-based fuels confirmed that horizontal ventilation, vertical ventilation, and positive pressure attack are different tactics and as such, produce different responses with regards to regrowth, stages of fire development, flow paths, and discrepancies between training and the fireground. Both wood-based and furniture fuels highlight the need to constantly assess both the inlet and exhaust openings during positive pressure attack to determine the effectiveness of the fan application. As the ventilation profile changes, positive pressure attack has the potential to become either more or less effective. The effectiveness of the positive pressure attack application is also exhaust dependent in that the size of the vents in the fire compartment must be large enough to reduce the pressure, allowing the pressure generated by the fan to overcome the pressure generated by the fire. This keeps the fire in the compartment and allows the exhaust vents to be unidirectional outflow. Wood-based fuels are consistent with the furniture fuels. As the mass of the wood-based fuels is increased with the addition of OSB to be closer to the mass of the furniture fuel load, the comparisons are closer in line with one another. The comparisons also highlight that positive pressure attack has the potential to draw fire into uninvolved areas if the exhaust vents are not made in the fire compartment. New flow paths can be established and cause conditions to deteriorate.

This research study into the fire service training environment generated experimental results which allowed for the development of training considerations for fire service instructors to utilize in live-fire evolutions. The comparison of wood-based fuels to synthetic furnishings seen on the fireground helps to bridge the gap between training and real world experience.

6.1 Future Research Needs

Only 12 experiments were conducted in this series with only two training fuel packages and a limited number of ventilation profiles. As such, more research is needed in different structures, especially those with multiple stories including those below grade. Each ventilation tactic (horizontal, vertical, and positive pressure) should be examined on different floors, in different room sizes, and in structures with different construction methods and finishes. These experiments were also conducted without any repeatability or examination of other variables such as suppression tactics. Further research should consider repeatability of ventilation profiles across similar fuel packages. Suppression should be studied in conjunction with the ventilation tactics to further determine the best means of coordination and if these principles hold true on the training ground with wood-based fuel packages. Consideration should also be given to different sized fuel loads and conducting tests with a consistent fuel mass, regardless of whether it is wood-based or furniture. This would further strengthen the comparison between the training ground and the fireground and provide instructors with a better understanding of how to maximize fidelity and minimize risk.

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Appendix A Fuel Load Details

Table A.1: Wood-Based Training Fuel Weights

Experiment #	Pallets (kg)	Straw (kg)	OSB (kg)
1	20.5, 19.4, 17.9	16.3	—
2	24.2, 19.2, 16.7	13.8	21.0, 21.1, 22.1
3	23.1, 20.2, 15.7	13.4	—
4	23.5, 16.0, 14.2	14.7	22.7, 22.1, 21.2
5	19.3, 19.2, 19.1	14.4	—
6	20.5, 18.6, 16.2	15.7	21.3, 21.0, 20.8
7	21.2, 16.9, 15.0	11.0	—
8	16.6, 15.8, 15.3	15.9	21.3, 21.1, 22.0
9	18.6, 18.5, 18.3	9.3	—
10	21.7, 20.5, 17.5	15.5	21.3, 21.1, 20.9
11	19.9, 18.6, 16.6	14.0	—
12	19.7, 19.3, 18.0	13.7	21.8, 21.4, 21.4

Table A.2: Furniture Dimensions and Weights: Horizontal Ventilation

Item	Length (in.)	Width (in.)	Height (in.)	Weight (kg)
Armoire	28	41	79	129.3
Sofa	72.5	36	33	77.5
Chair	35	32.5	32.5	27.2
End Table	24	27	24.3	10.4
Coffee Table	20	36	19.5	13.6
Television	24	27	24	32.6
Brass Picture	30	1	26	3.9
Blue Picture	38.5	1	21.5	4.3
Lamp Shade	20	10	9.5	0.3
Curtains	—	—	—	2.9
Mattress	60	78	7.5	29.7
Box Spring	60	78	7.5	28.6
Light Brown Dresser	71.5	19	23.3	63.5
Dark Brown Dresser	71.7	20	24	59.4
Mirror	28	1	46.5	11.3
Headboard	60.5	1.3	20	15.9
Comforter	2	86	92	2.3
Pillows	6	20	26	0.5

Table A.3: Furniture Dimensions and Weights: Vertical Ventilation

Item	Length (in.)	Width (in.)	Height (in.)	Weight (kg)
4 Drawer Chest	44	24	35	97.3
Green Stripe Sofa	70	36	35.5	80.8
Rose Chair	34	34	30	22
Rose Autumn	28	20	16	8.8
Coffee Table	42	20	19	16.7
Table Lamp w/ Shade	4	4	28	3.1
TV Set	38	5	25	21.5
End Table	26	26	25.8	13.1
Picture	31	1.5	21.5	3.2
Curtains	94	132	—	8.1
Mattress	79	59	7.8	29.3
Box Spring	79	59	7.5	31.7
Nightstand	22	18	25	8.9
2 Drawer Chest	23.8	18.5	23.8	26.1
6 Drawer Wood Dresser	54	18	32	56.6
Mirror	28	1	48	13.1
Headboard	72	1.3	26	18.2
Pillows	24	16	3	0.7
Mattress Pad	75	69	—	1.1
Memory Foam Mattress Topper	56	75	1.5	1.9
Bed Skirt	60	81	14	0.5
Fitted Sheet	60	80	14	0.7
Flat Sheet	120	90	—	0.5
Comforter	90	86	—	2.1
Pillow Cases	30	24	—	0.2

Table A.4: Furniture Dimensions and Weights: Positive Pressure Ventilation

Item	Length (in.)	Width (in.)	Height (in.)	Weight (kg)
Nightstand	27	17	23.5	26.9
Box Spring	79	52.5	9	19.1
Mattress	80	53	8	24.0
Comforter	92	104	—	—
Standard Pillow	24	16	3	0.7
Flat Sheet	98	83	—	1.6
Headboard	54	18	2.5	15.5
Dresser	44.5	24	35.5	96.4
Ottoman	23	18	16.5	7.3
Round End Table	24	24	22	14.7
Coffee Table	30	18	18	11.3
Lamp & Shade	12	12	22	2.9
Chair (Yellow)	30	30.5	34	15.8
Chair (Brown)	32	32	33	37.2
Sleeper Sofa (Green)	84	36.5	33	94.3
Sleeper Sofa (Orange)	65	35.5	31.5	65.8
Curtain	—	225	100	8.2

Appendix B Dimensioned Floor Plans

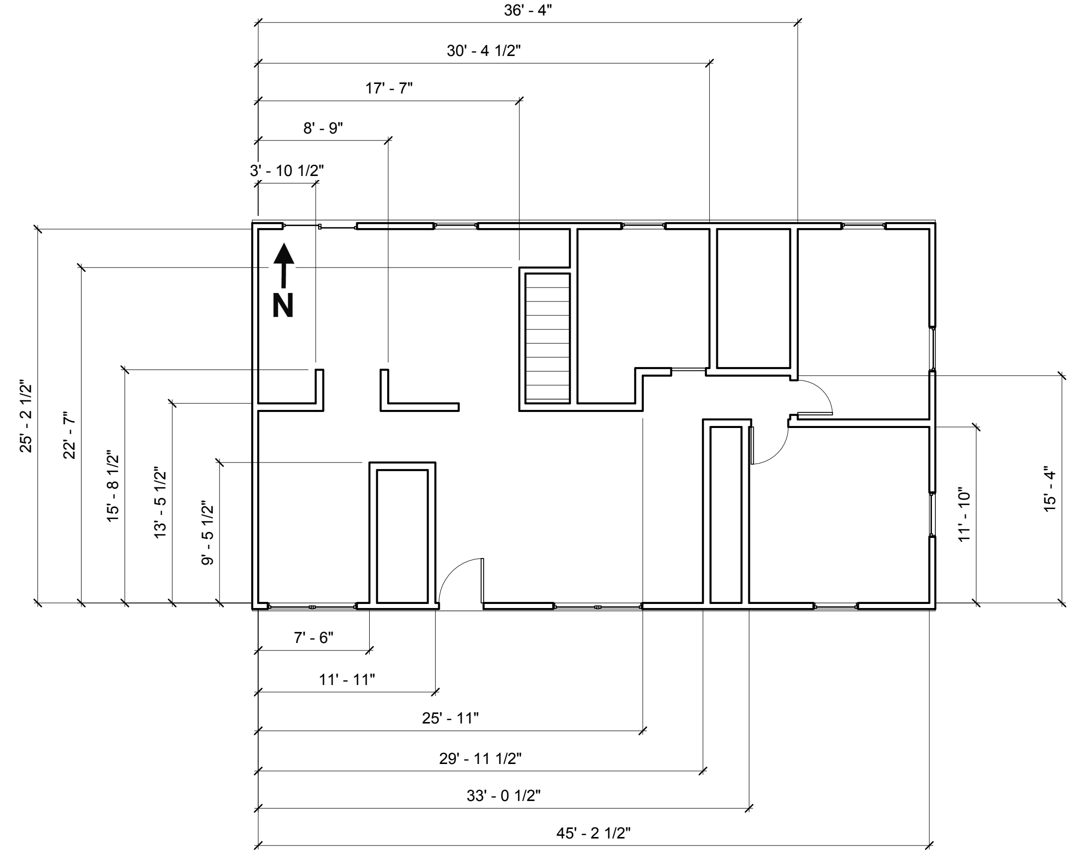

Figure B.1: Fully Dimensioned Floor Plan of the First Floor

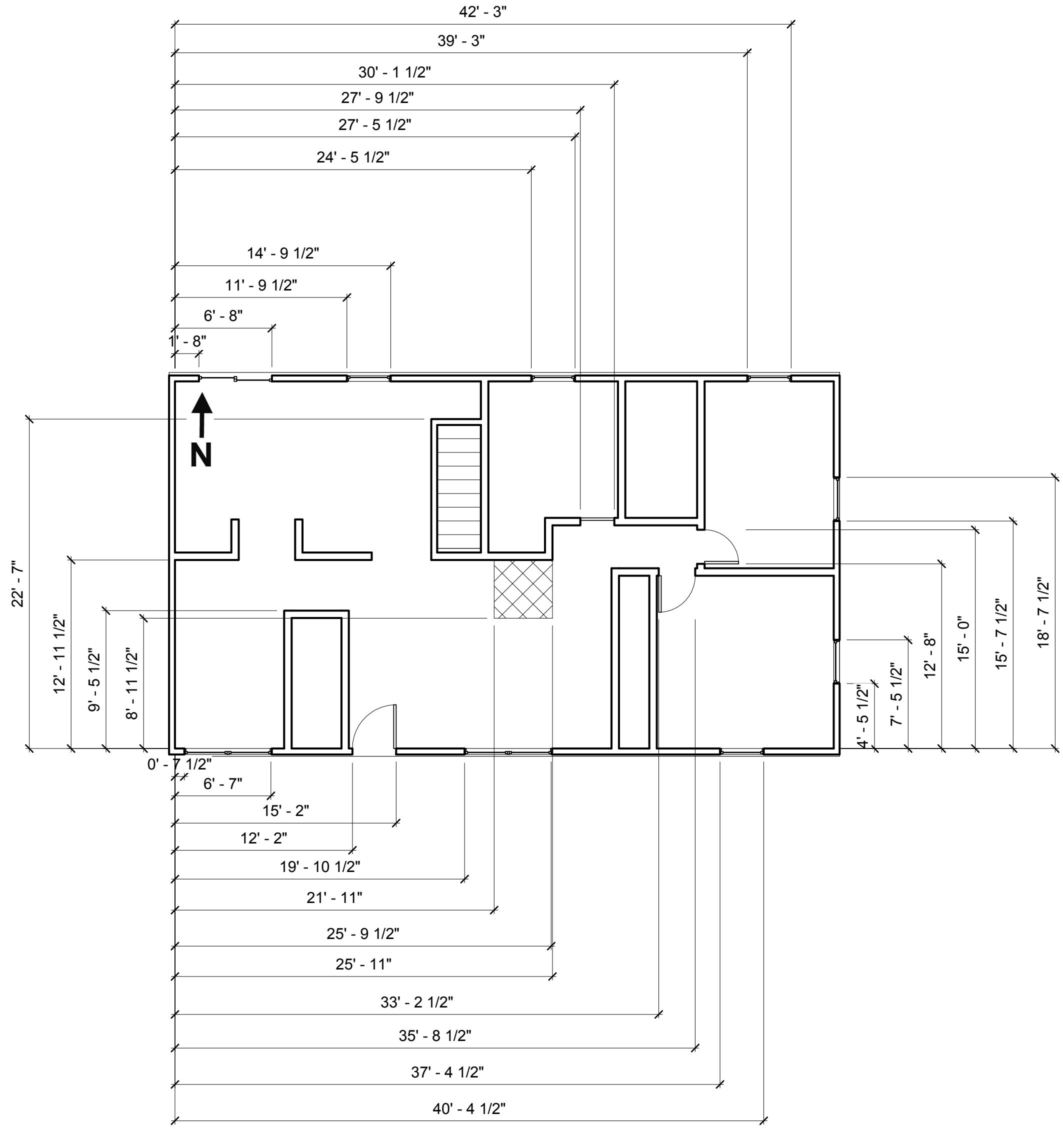

Figure B.2: Fully Dimensioned Floor Plan of the First Floor Vent Locations

Appendix C Experimental Results

C.1 Experiment 1 Data

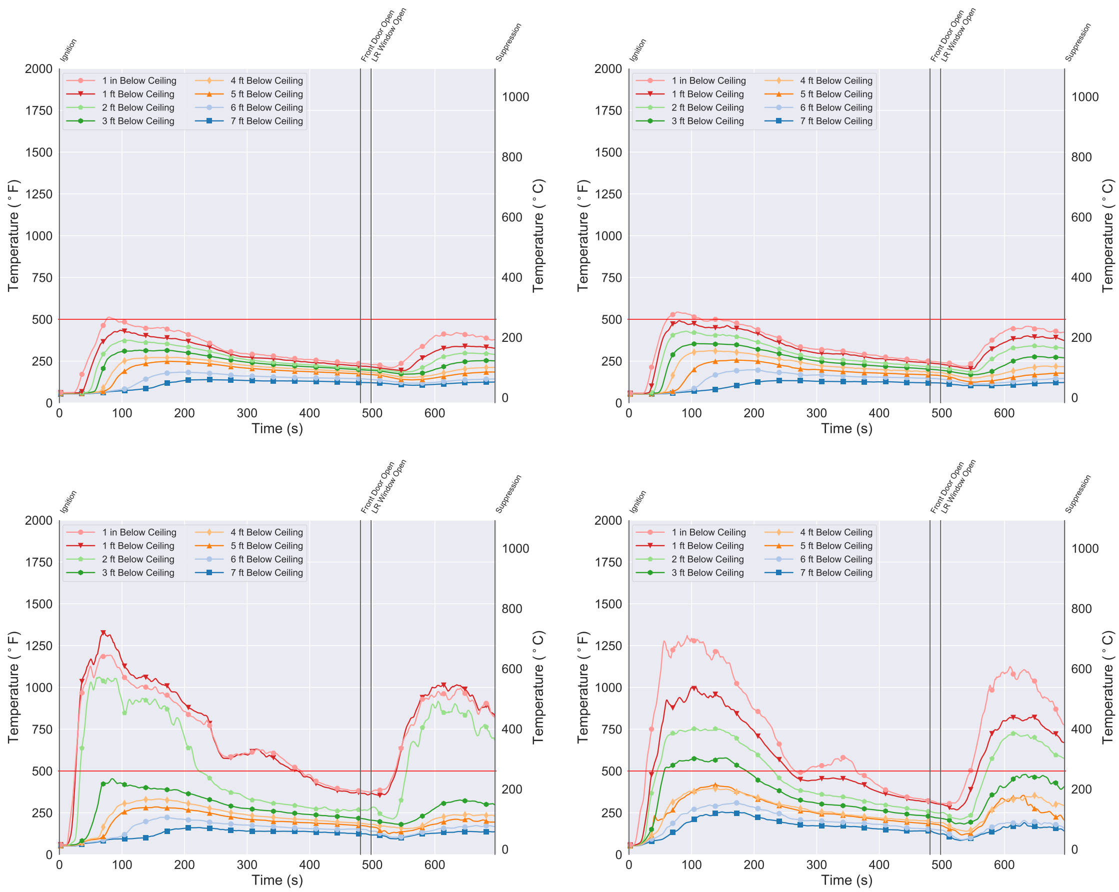

Figure C.1: Experiment 1 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

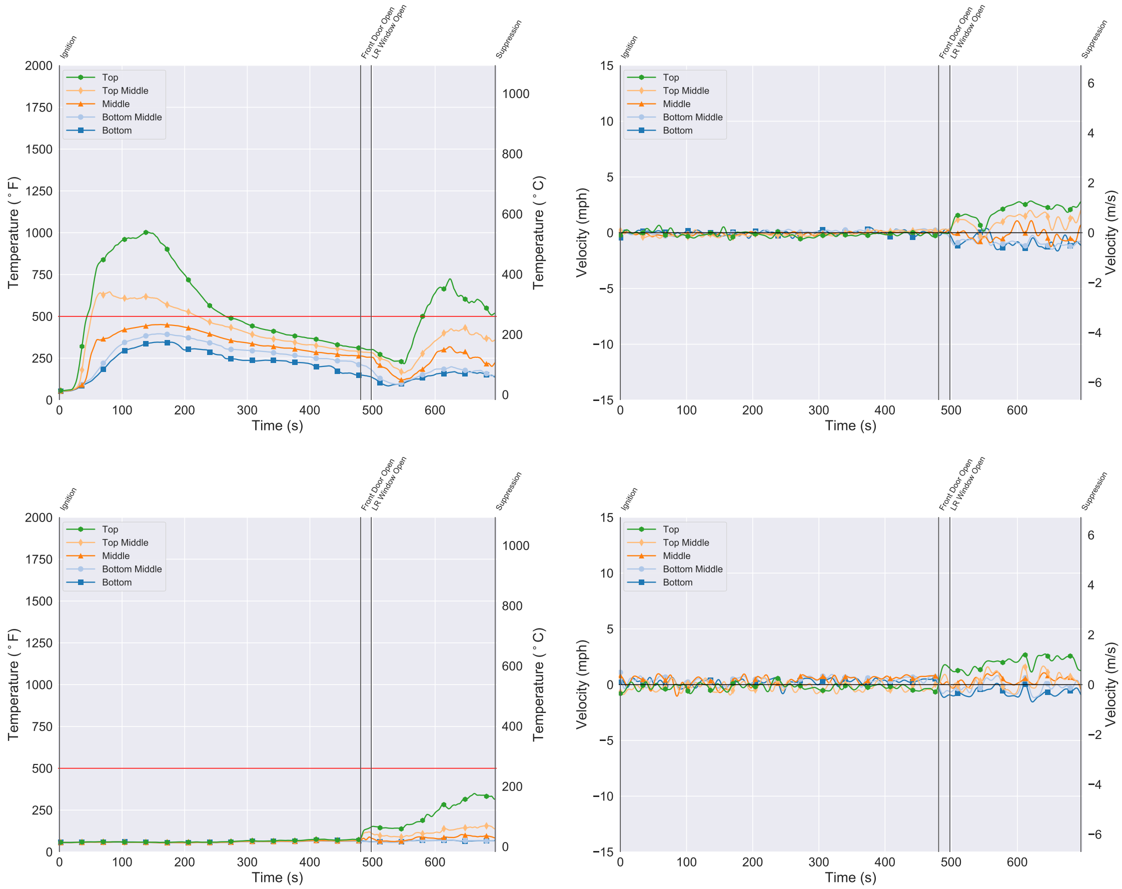

Figure C.2: Experiment 1 temperatures and gas velocities for the Living Room window (top) and Front Door (bottom).

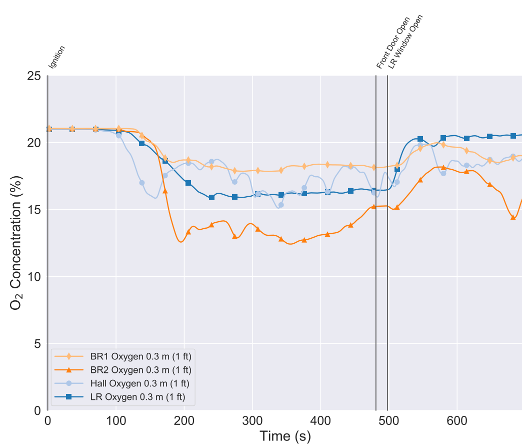

Figure C.3: Experiment 1 oxygen concentrations.

C.2 Experiment 2 Data

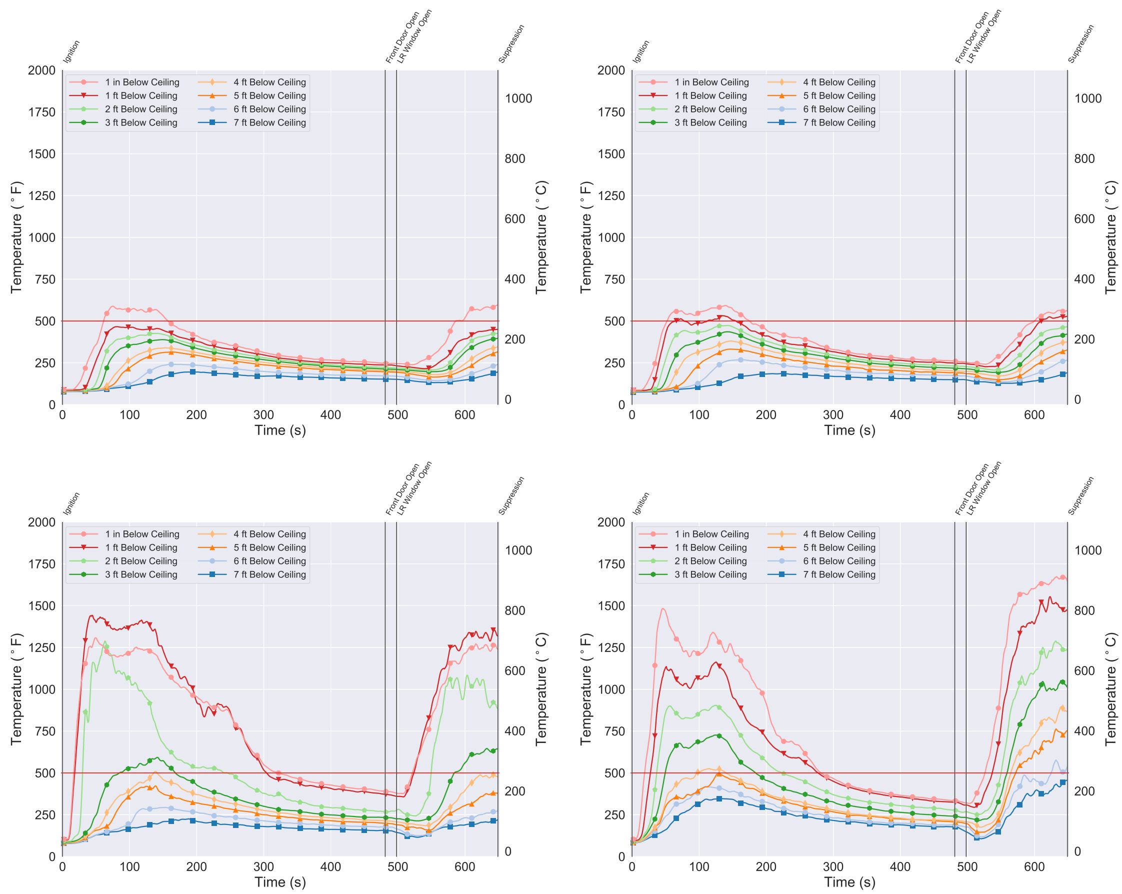

Figure C.4: Experiment 2 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

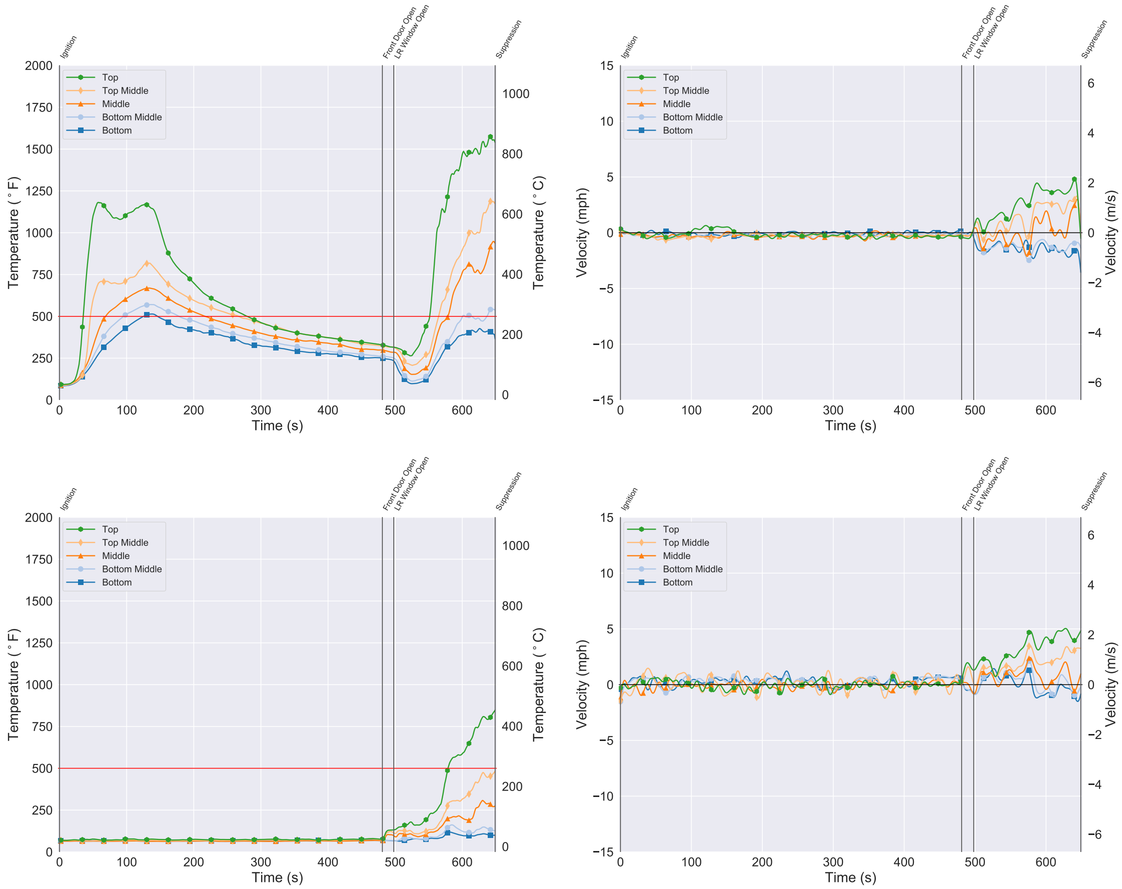

Figure C.5: Experiment 2 temperatures and gas velocities for the Living Room window (top) and Front Door (bottom).

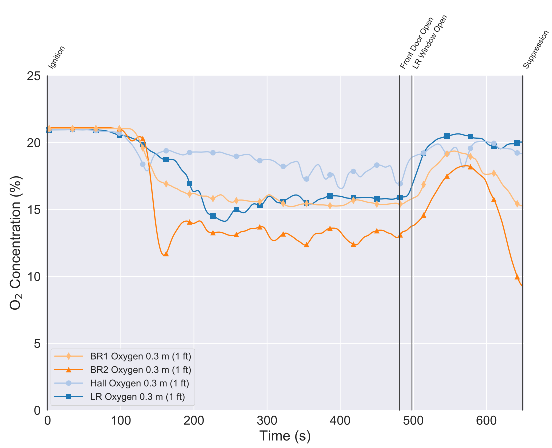

Figure C.6: Experiment 2 oxygen concentrations.

C.3 Experiment 3 Data

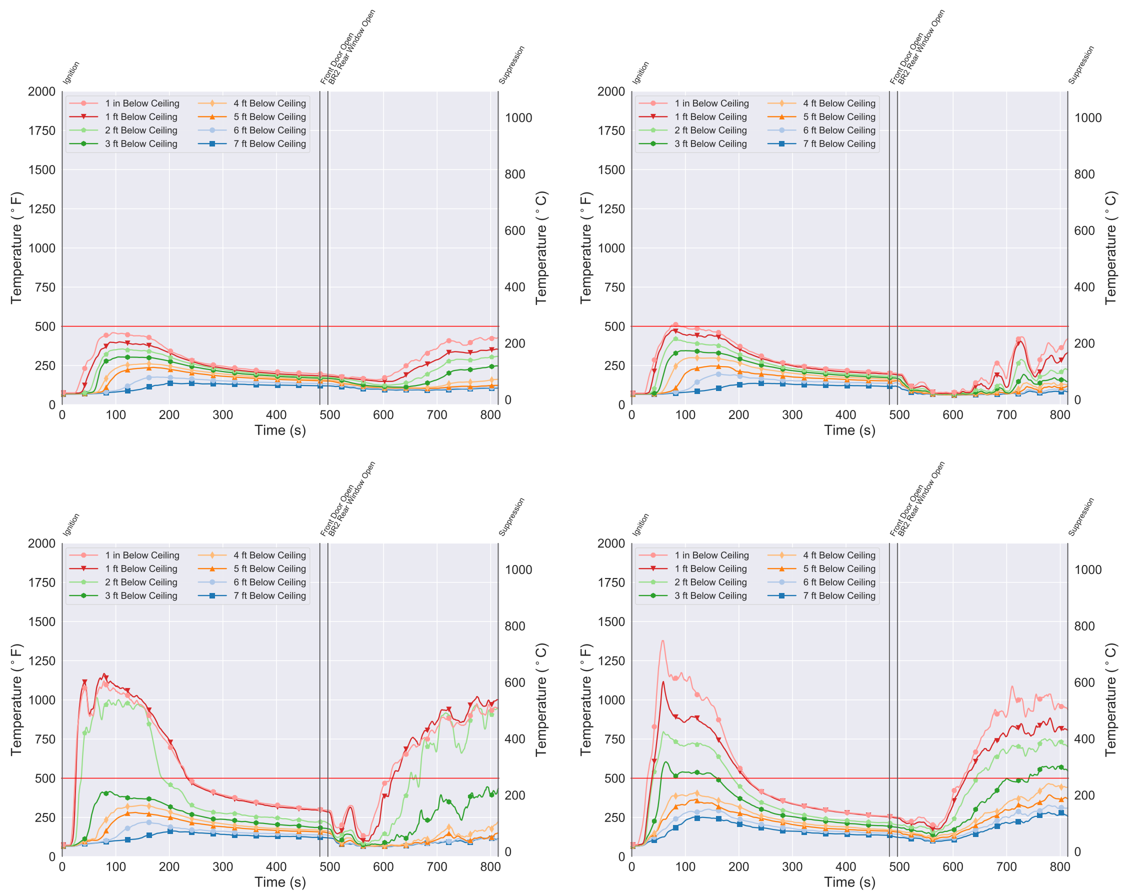

Figure C.7: Experiment 3 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

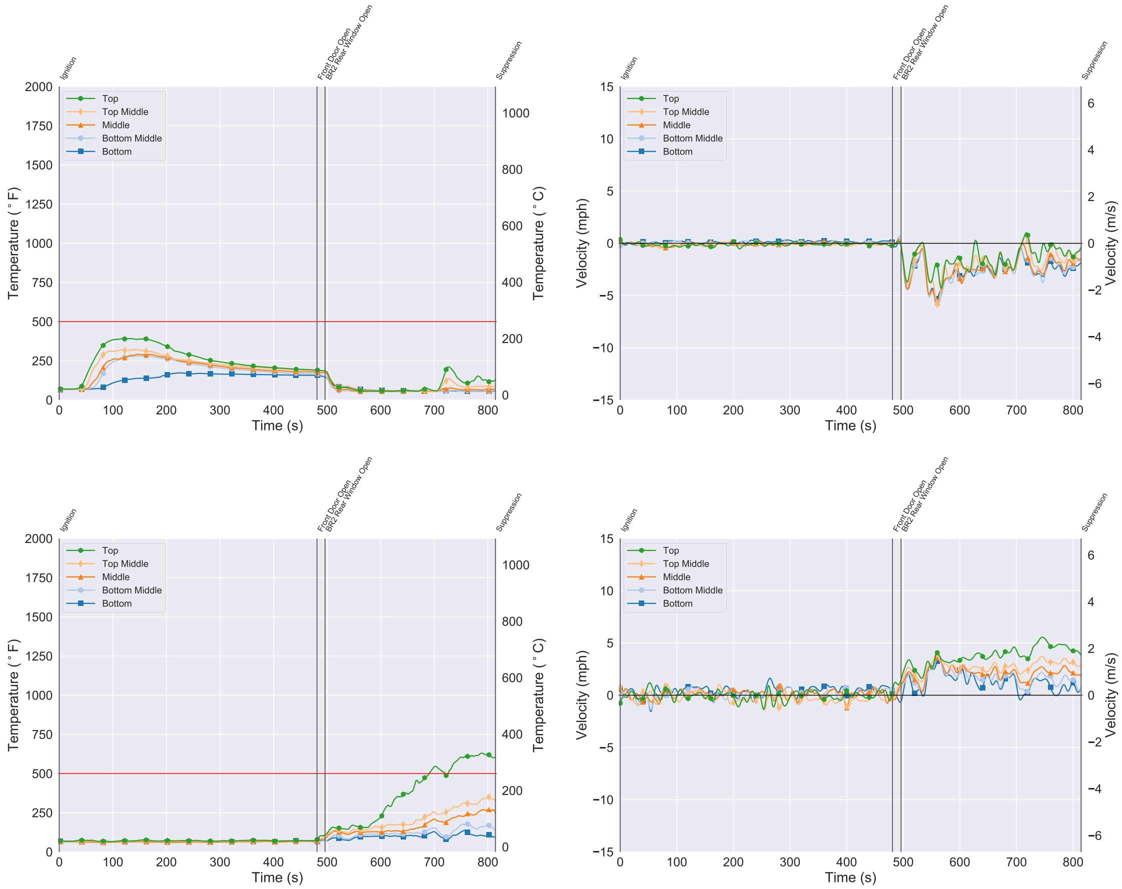

Figure C.8: Experiment 3 temperatures and gas velocities for the Bedroom 2 window (top) and Front Door (bottom).

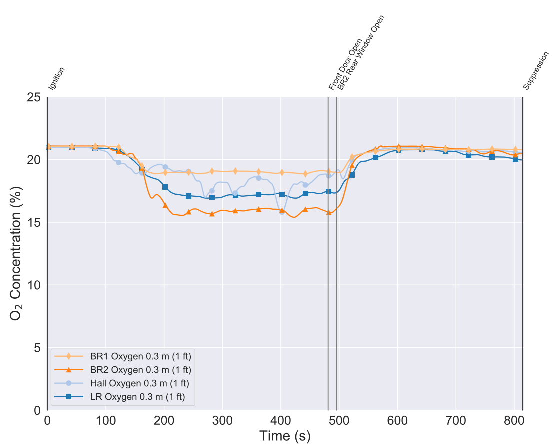

Figure C.9: Experiment 3 oxygen concentrations.

C.4 Experiment 4 Data

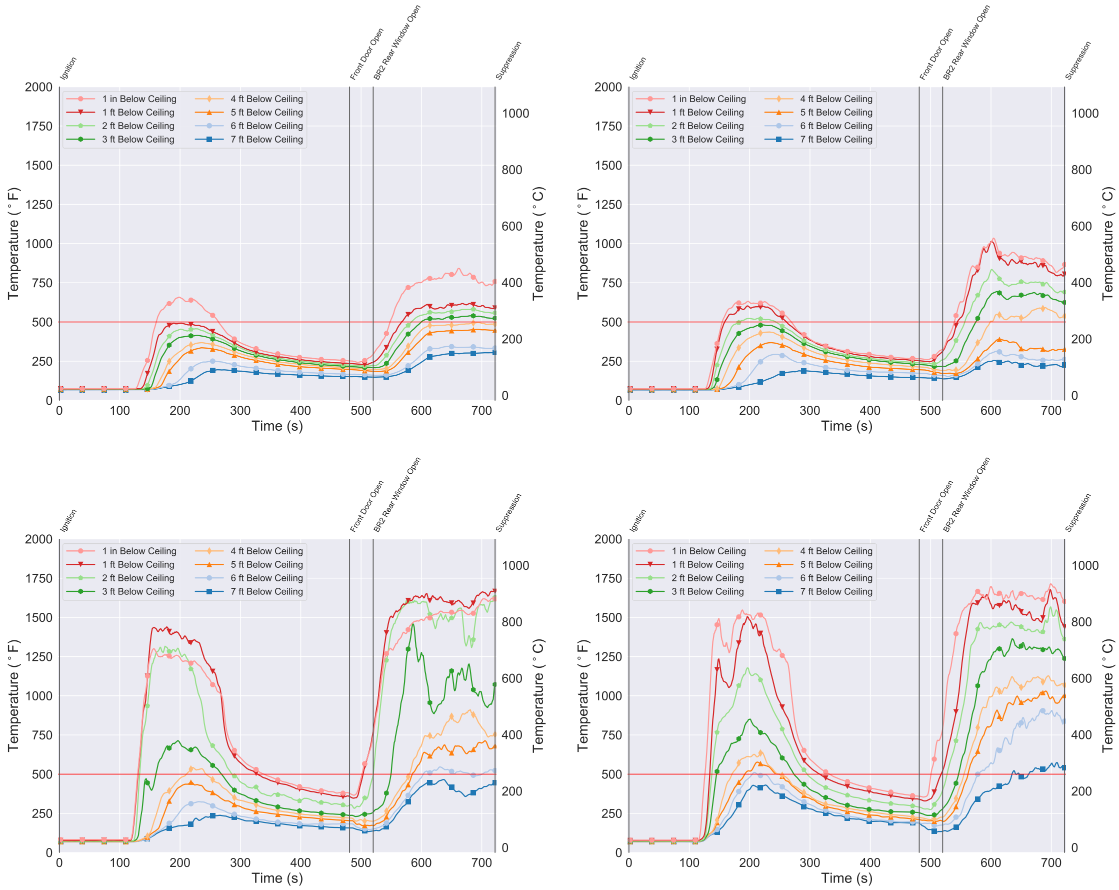

Figure C.10: Experiment 4 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

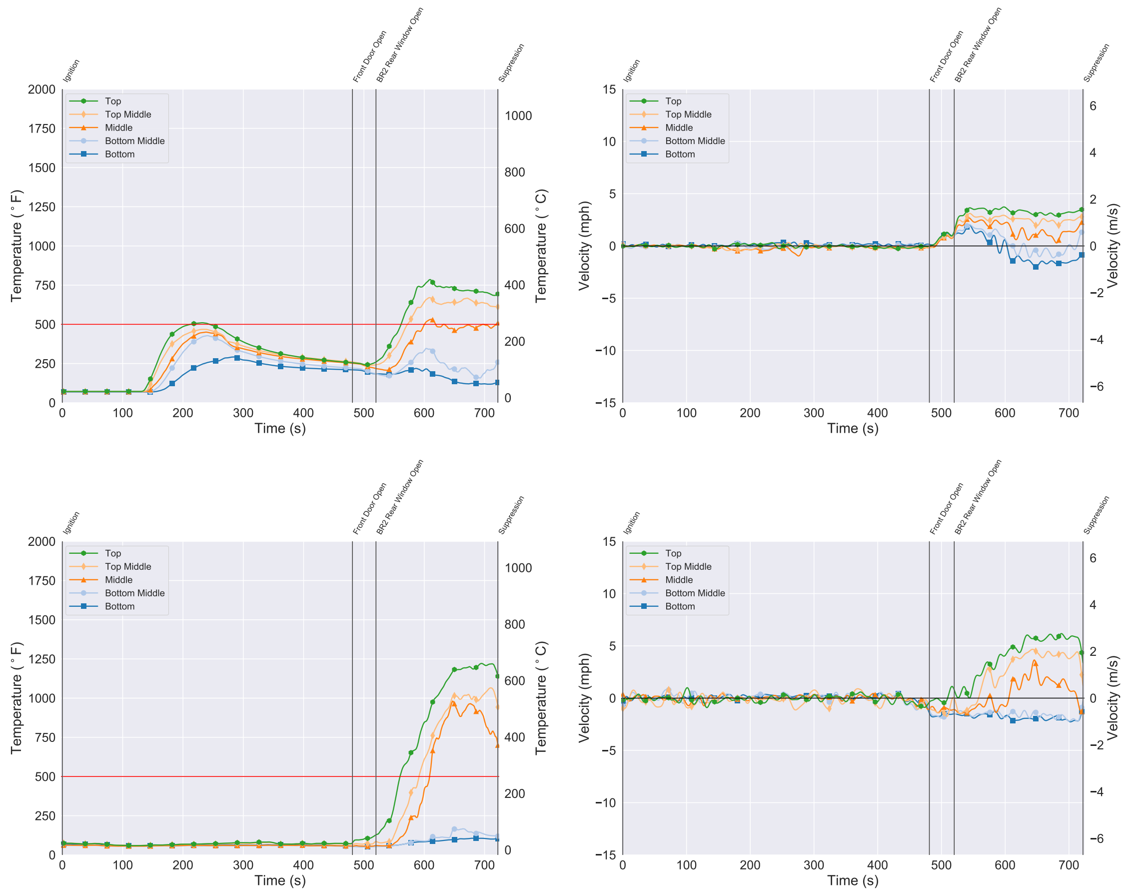

Figure C.11: Experiment 4 temperatures and gas velocities for the Bedroom 2 window (top) and Front Door (bottom).

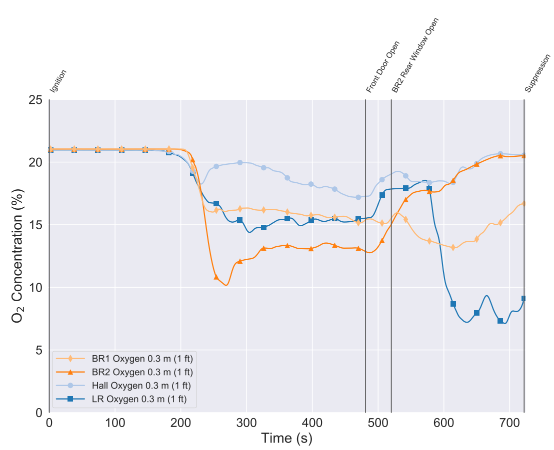

Figure C.12: Experiment 4 oxygen concentrations.

C.5 Experiment 5 Data

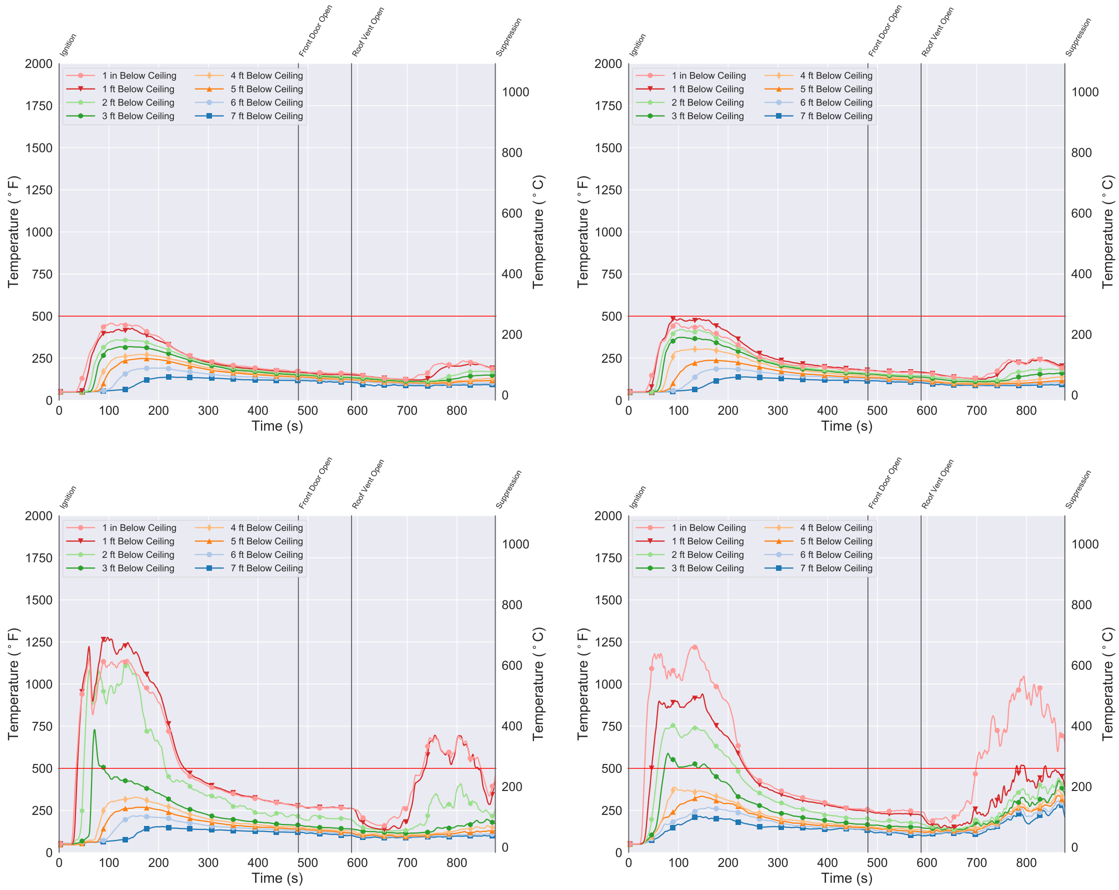

Figure C.13: Experiment 5 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

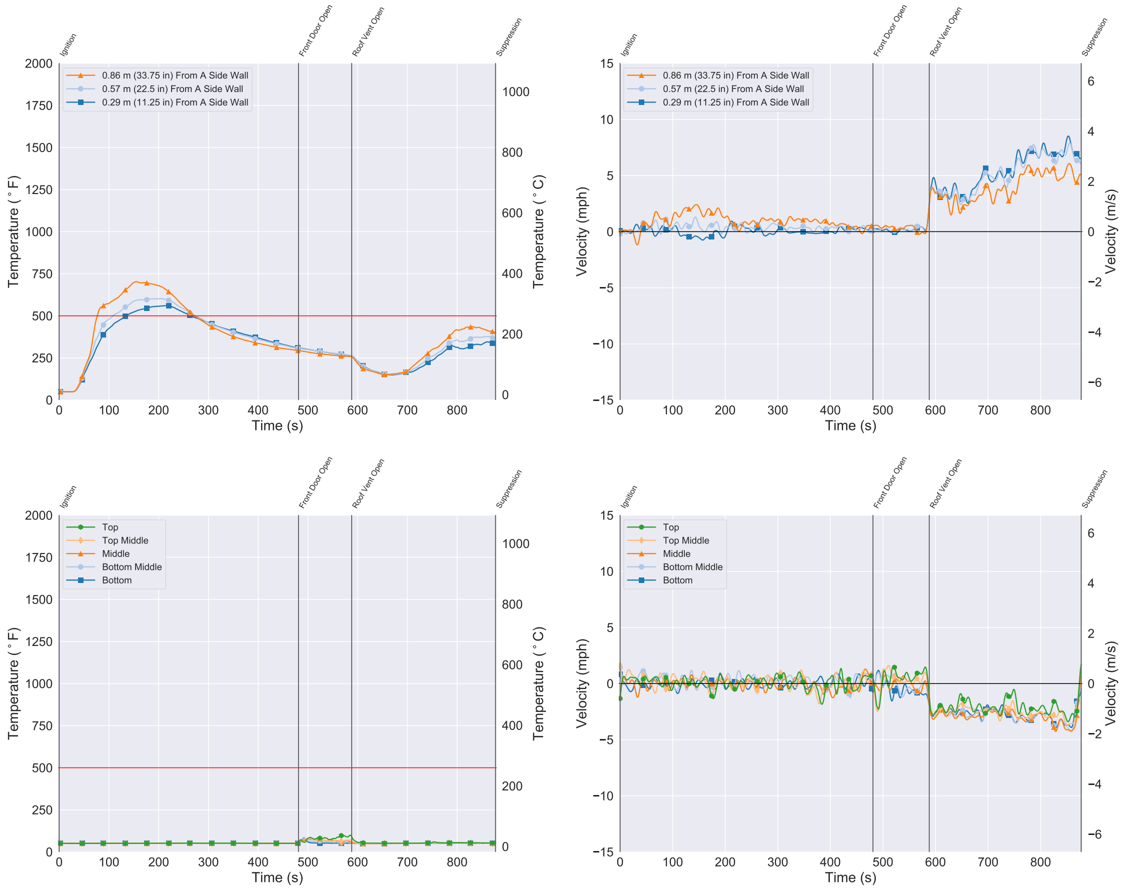

Figure C.14: Experiment 5 temperatures and gas velocities for the Roof Vent (top) and Front Door (bottom).

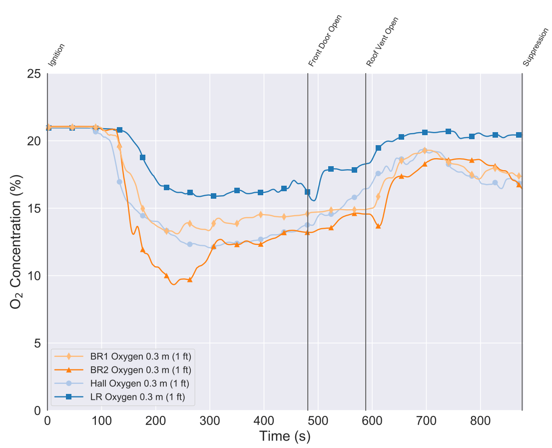

Figure C.15: Experiment 5 oxygen concentrations.

C.6 Experiment 6 Data

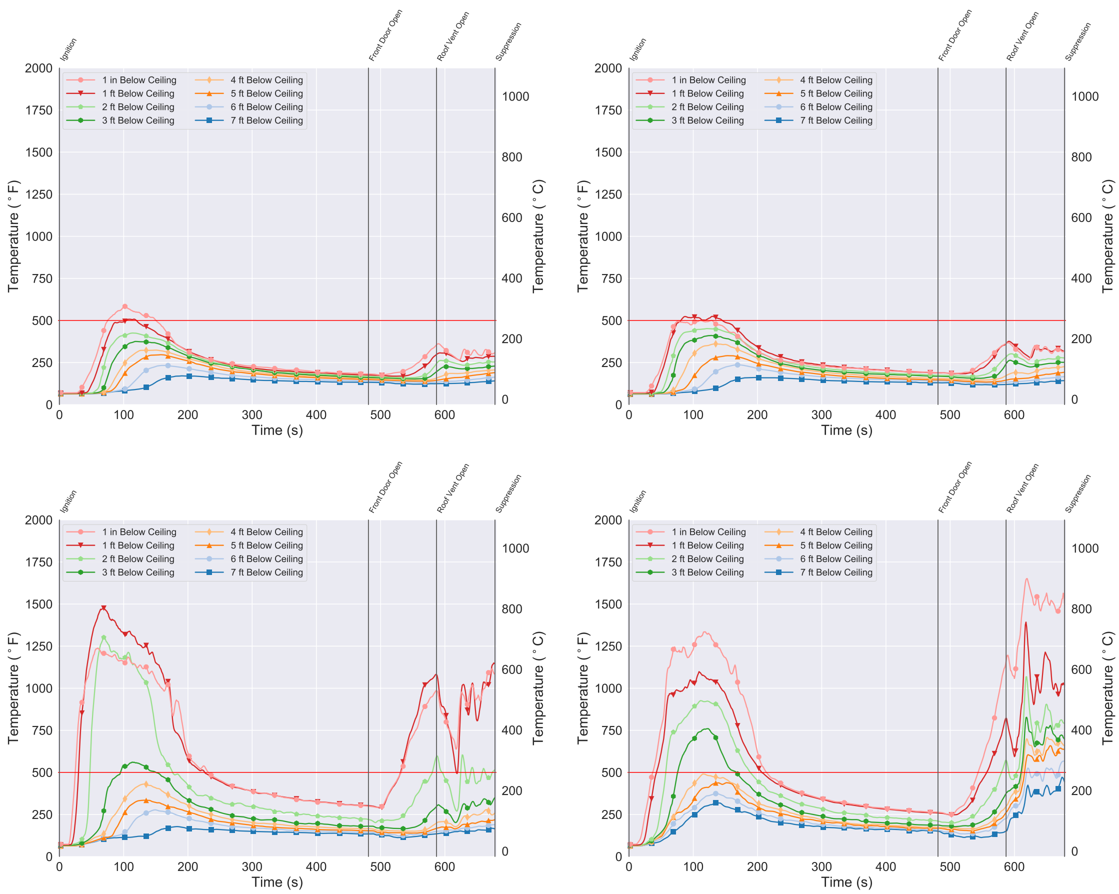

Figure C.16: Experiment 6 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

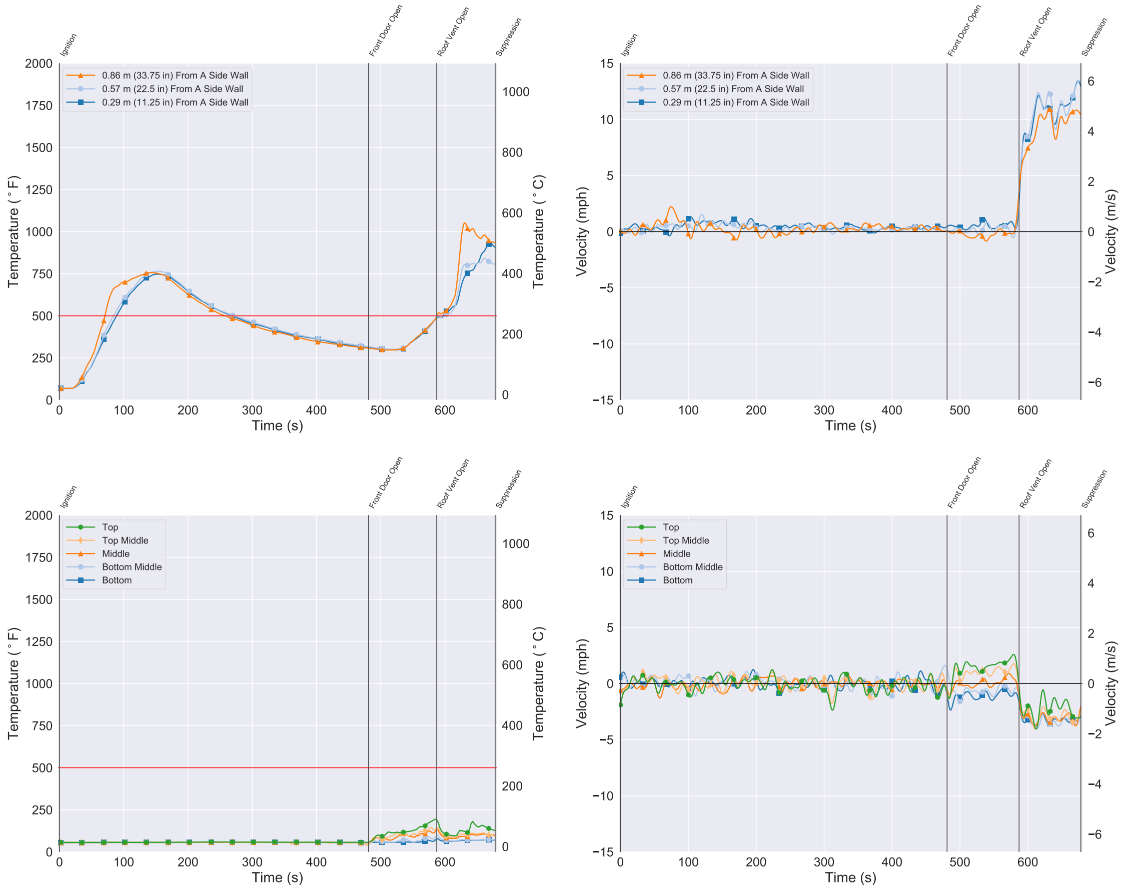

Figure C.17: Experiment 6 temperatures and gas velocities for the Roof Vent (top) and Front Door (bottom).

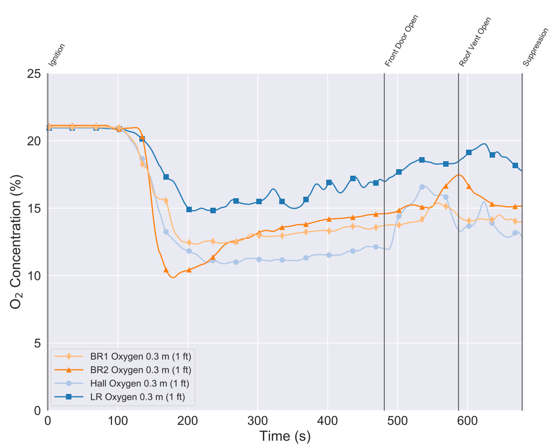

Figure C.18: Experiment 6 oxygen concentrations.

C.7 Experiment 7 Data

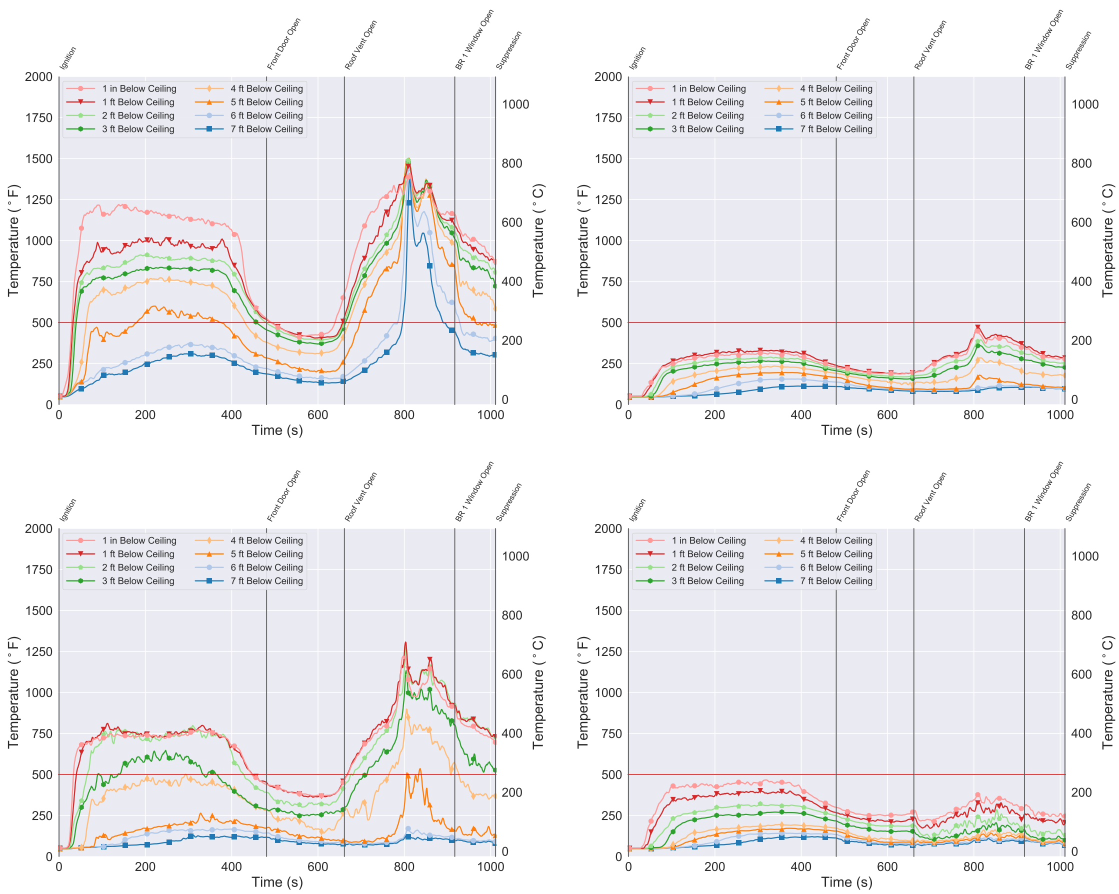

Figure C.19: Experiment 7 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

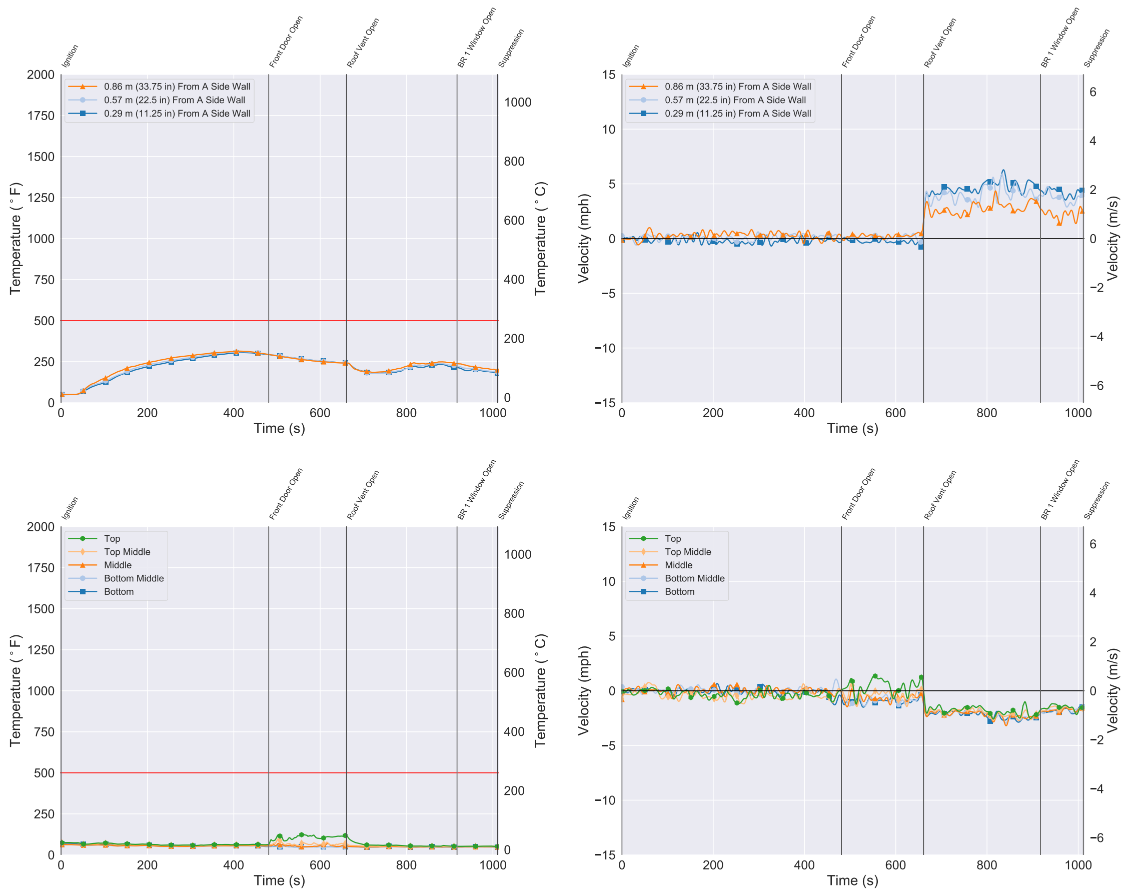

Figure C.20: Experiment 7 temperatures and gas velocities for the Roof Vent (top) and Front Door (bottom).

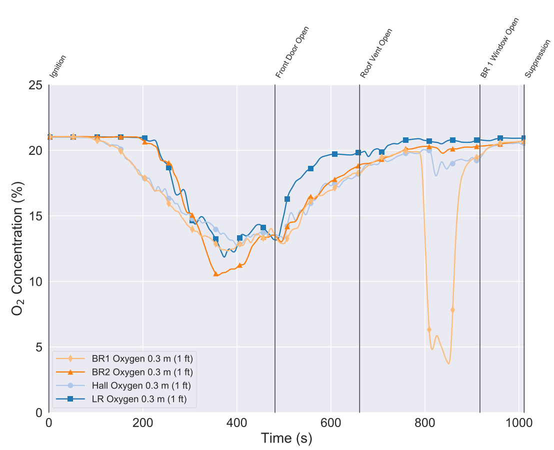

Figure C.21: Experiment 7 oxygen concentrations.

C.8 Experiment 8 Data

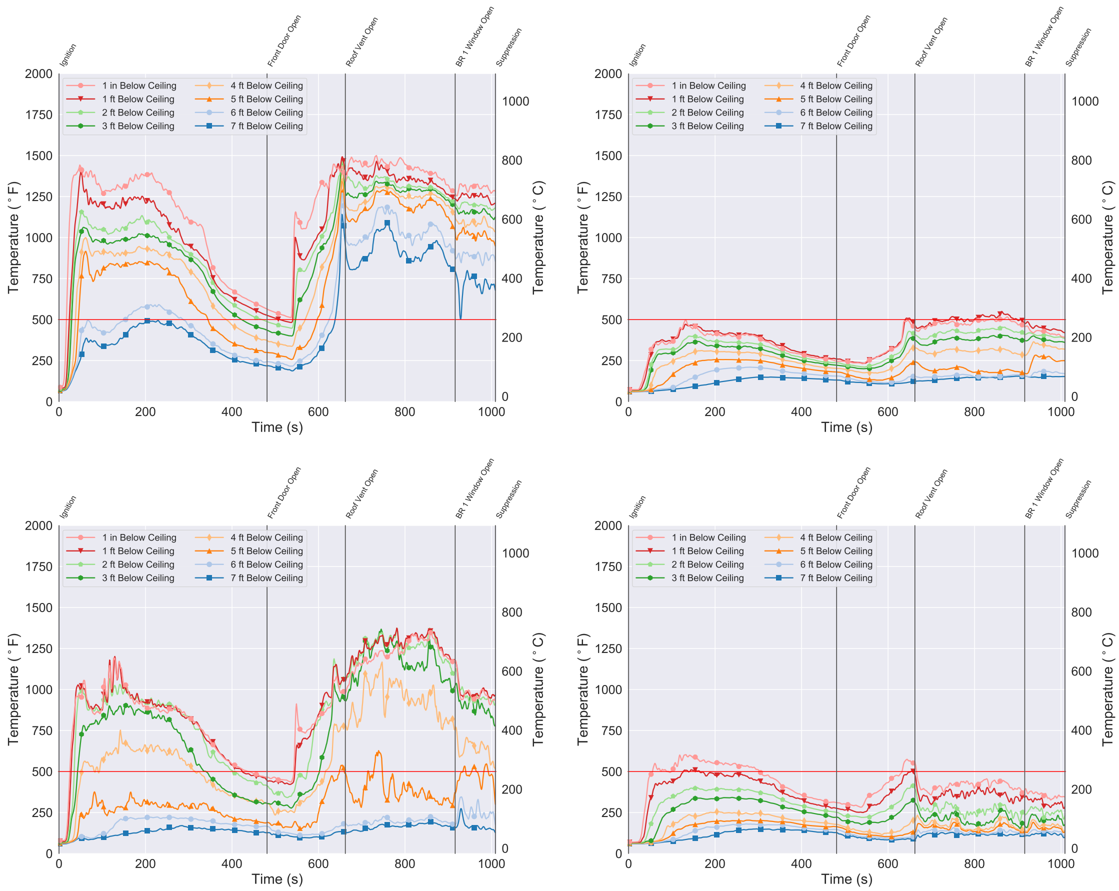

Figure C.22: Experiment 8 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

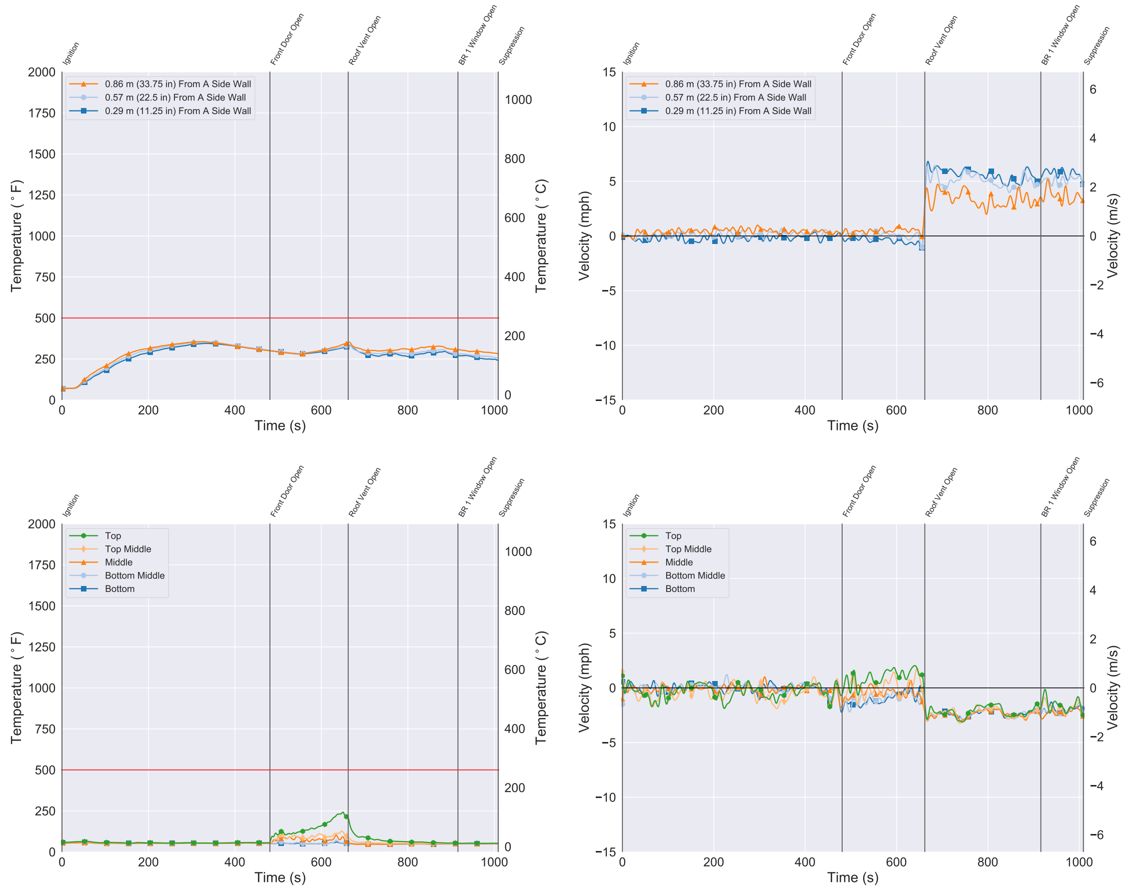

Figure C.23: Experiment 8 temperatures and gas velocities for the Roof Vent (top) and Front Door (bottom).

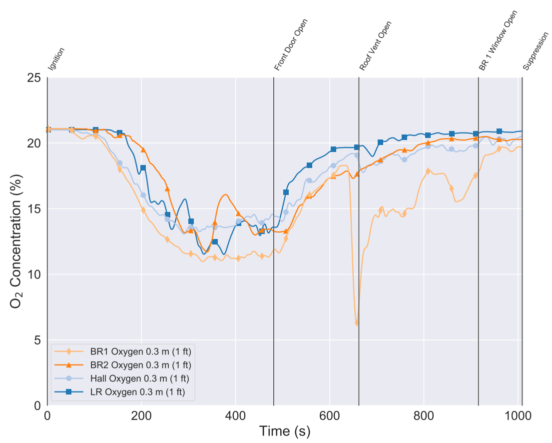

Figure C.24: Experiment 8 oxygen concentrations.

C.9 Experiment 9 Data

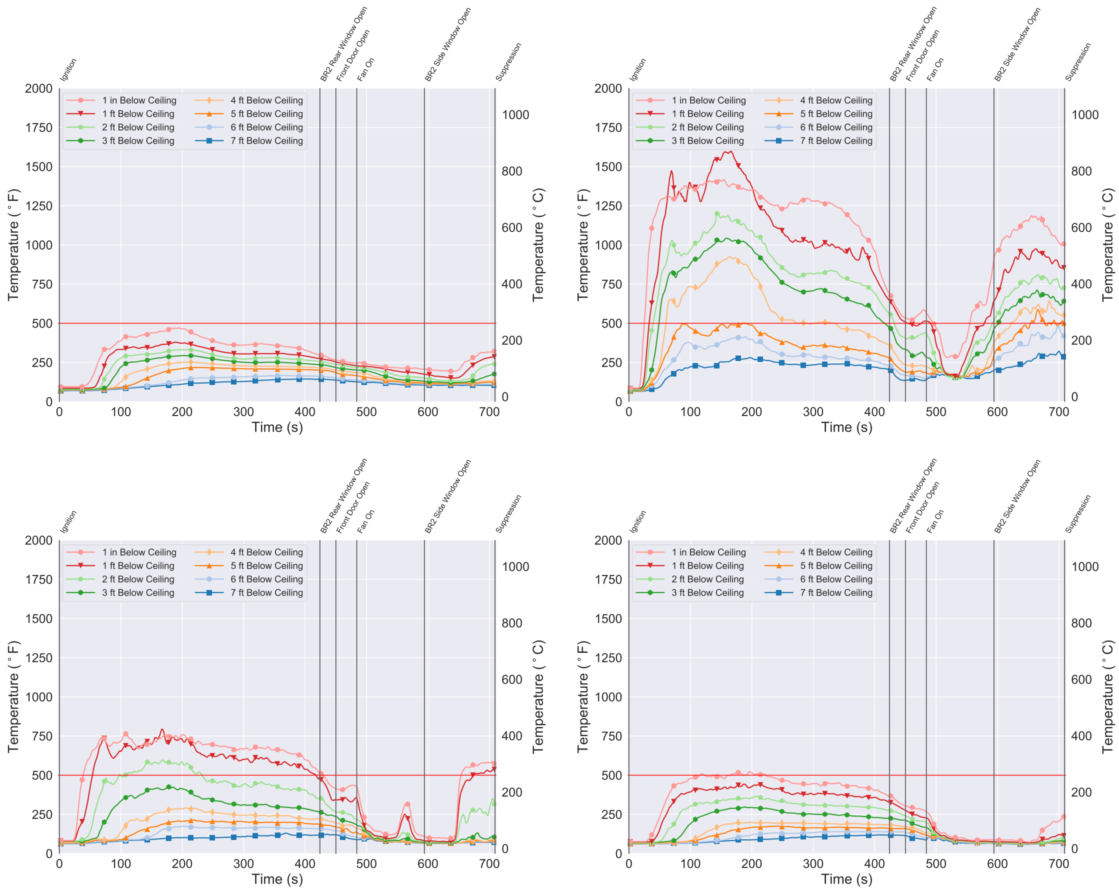

Figure C.25: Experiment 9 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

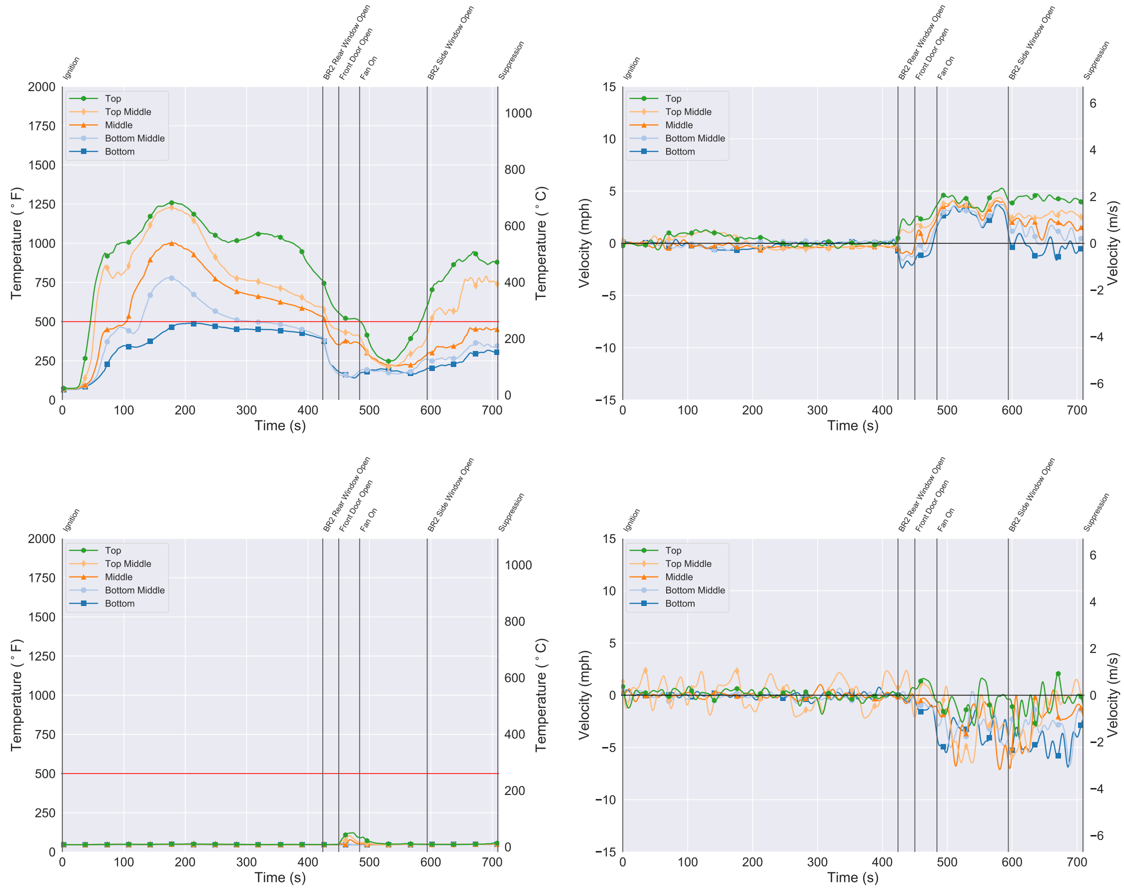

Figure C.26: Experiment 9 temperatures and gas velocities for the Bedroom 2 Window (top) and Front Door (bottom).

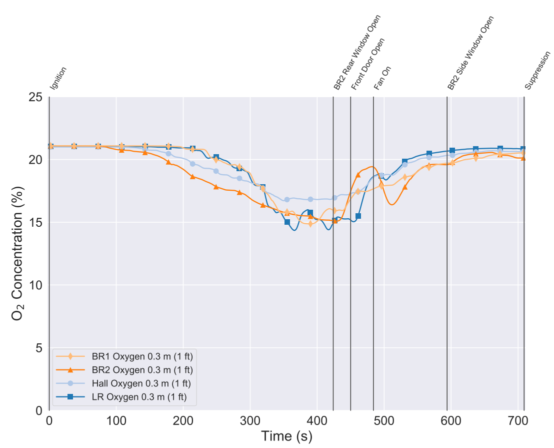

Figure C.27: Experiment 9 oxygen concentrations.

C.10 Experiment 10 Data

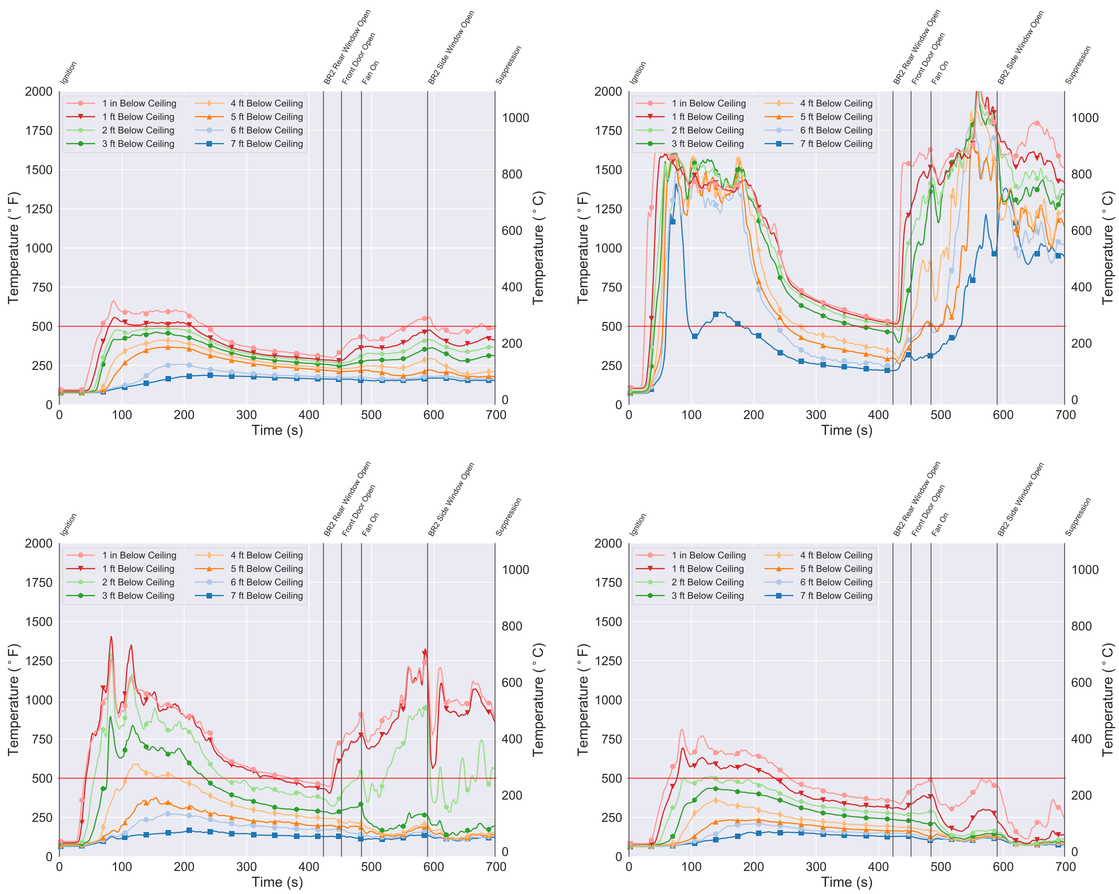

Figure C.28: Experiment 10 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

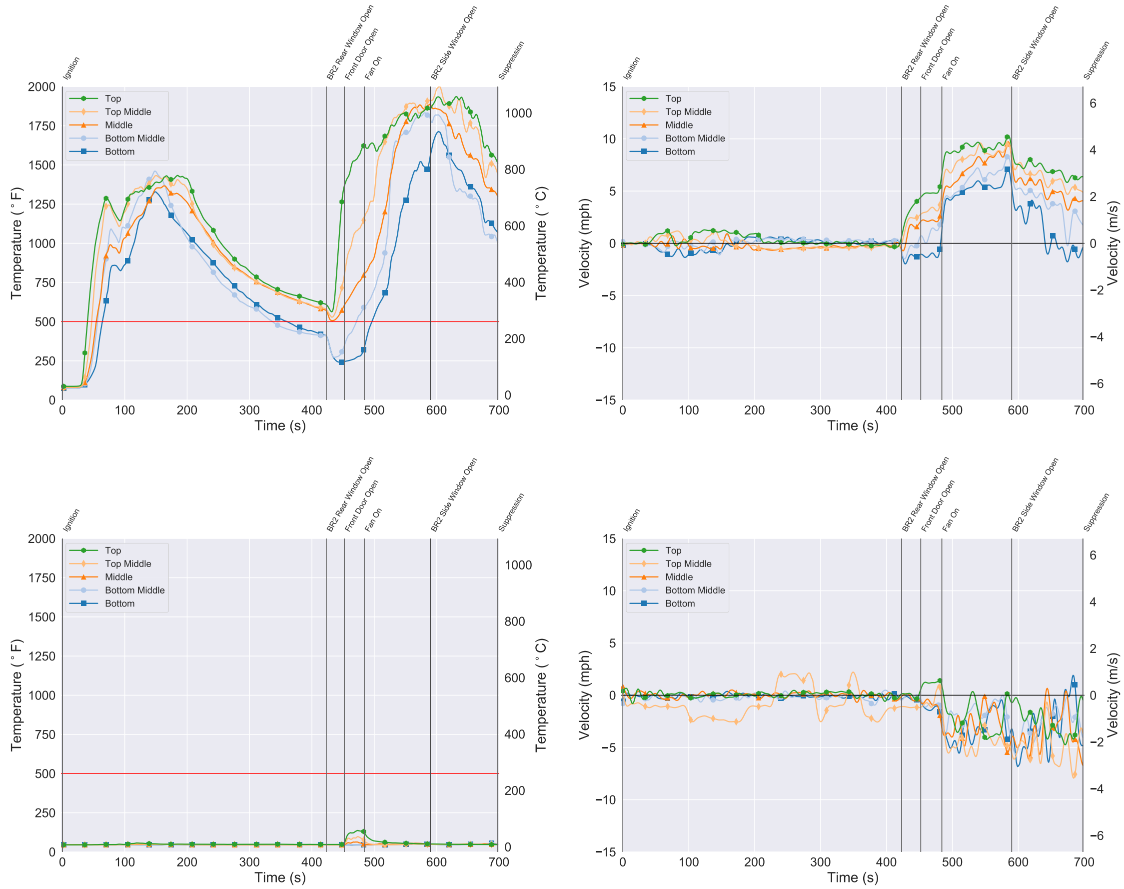

Figure C.29: Experiment 10 temperatures and gas velocities for the Bedroom 2 Window (top) and Front Door (bottom).

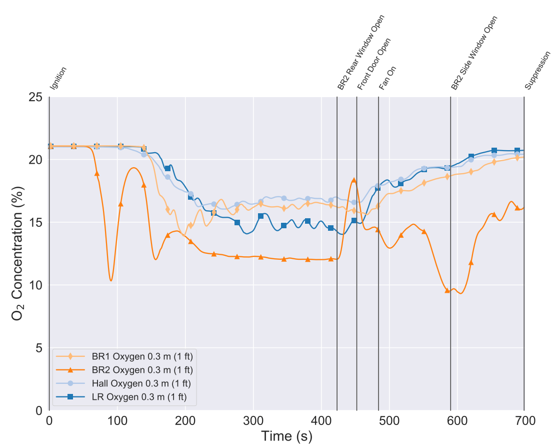

Figure C.30: Experiment 10 oxygen concentrations.

C.11 Experiment 11 Data

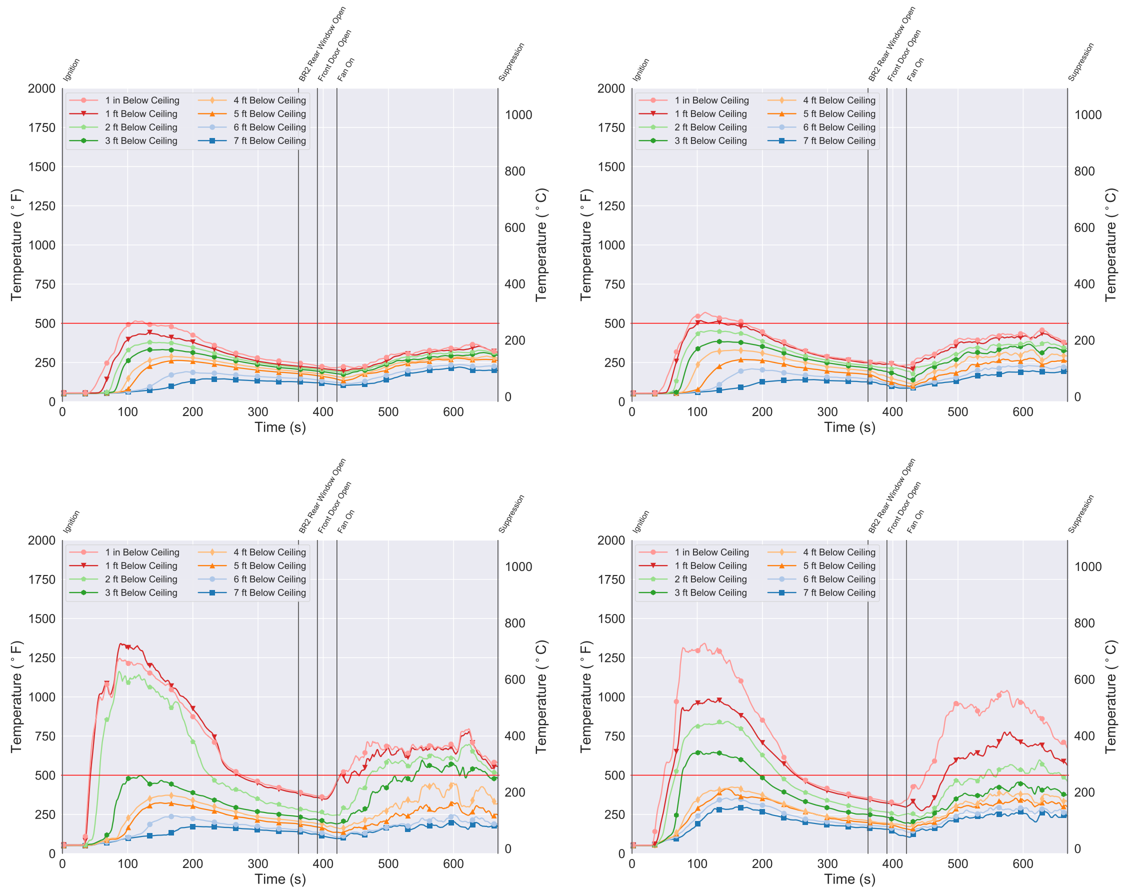

Figure C.31: Experiment 11 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

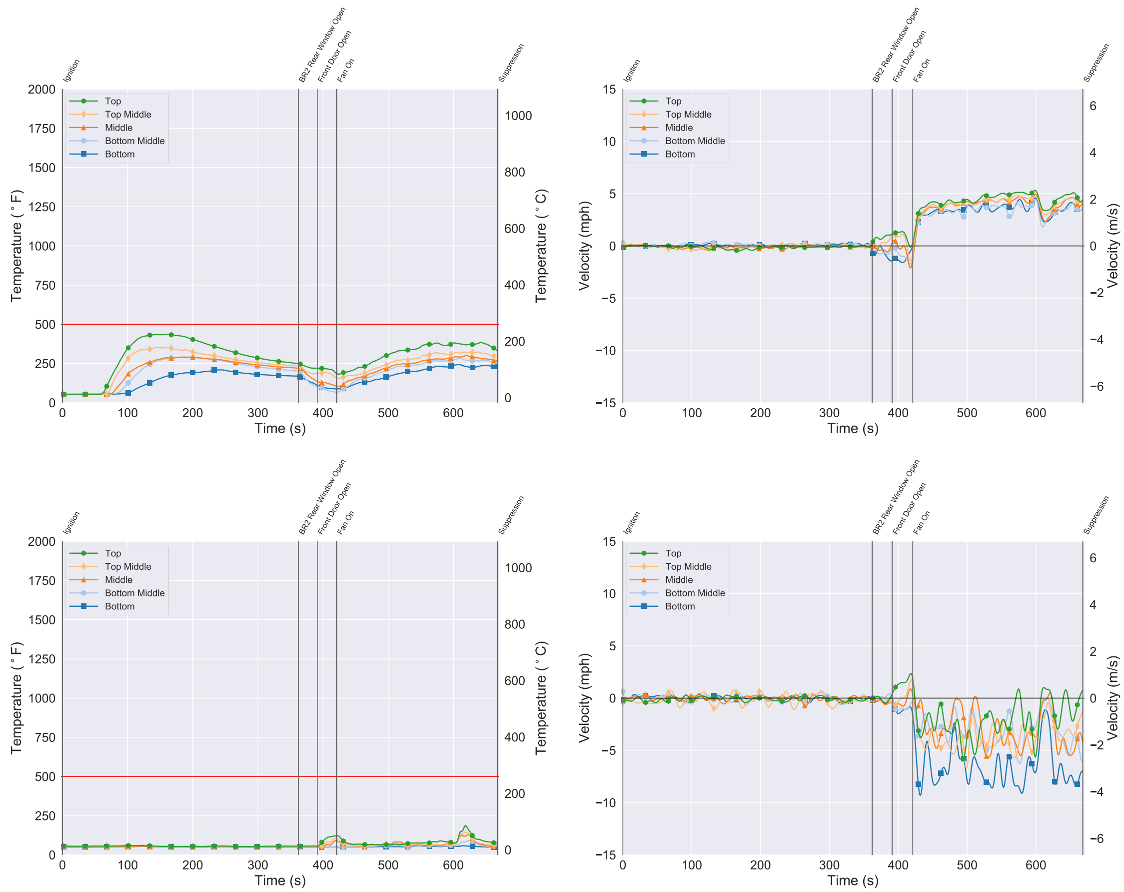

Figure C.32: Experiment 11 temperatures and gas velocities for the Bedroom 2 Window (top) and Front Door (bottom).

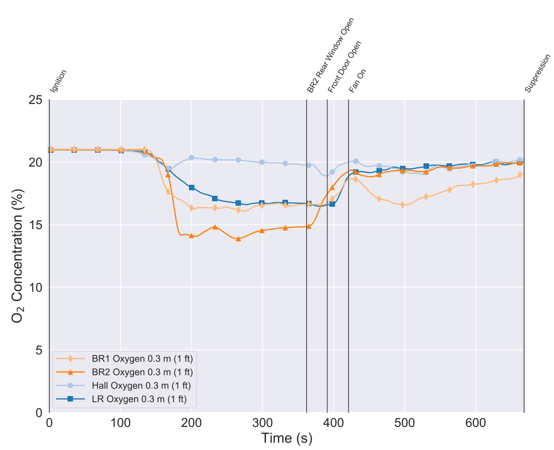

Figure C.33: Experiment 11 oxygen concentrations.

C.12 Experiment 12 Data

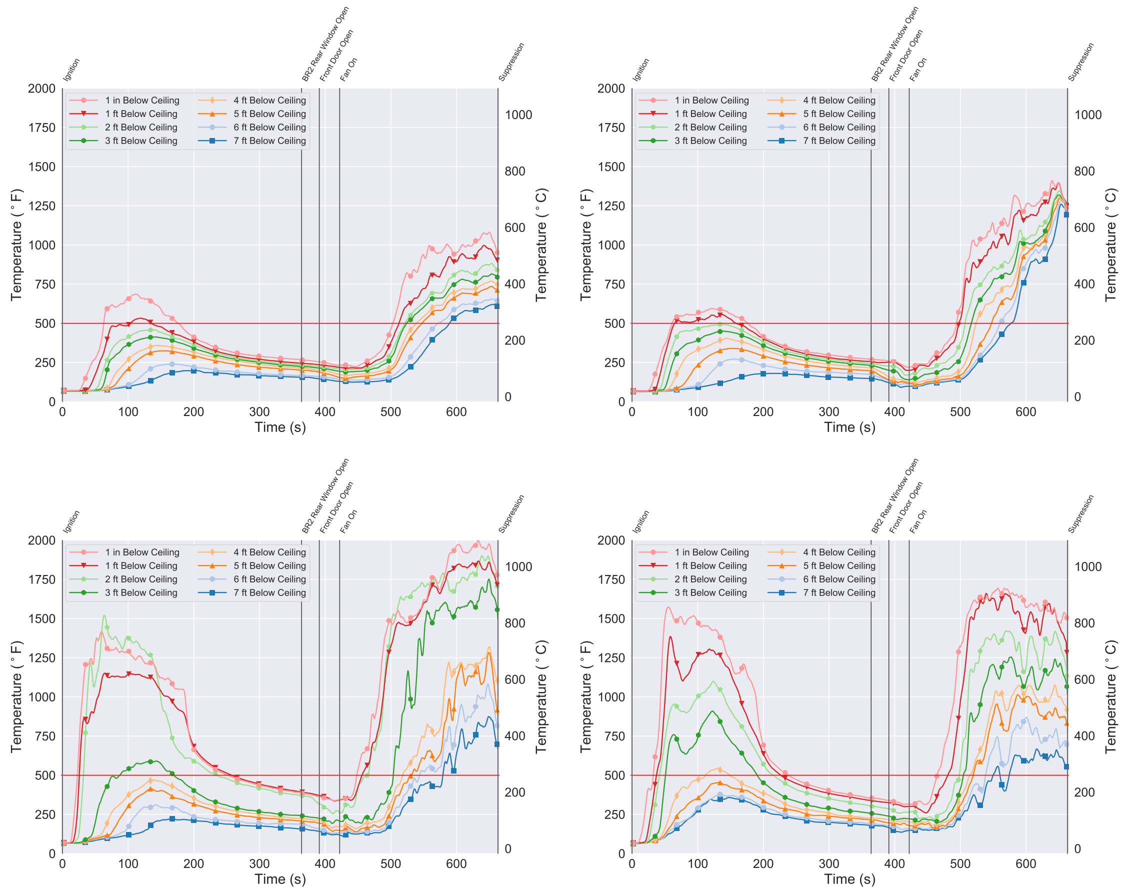

Figure C.34: Experiment 12 temperatures for Bedroom 1 (top left), Bedroom 2 (top right), Hallway (bottom left), and Living Room (bottom right).

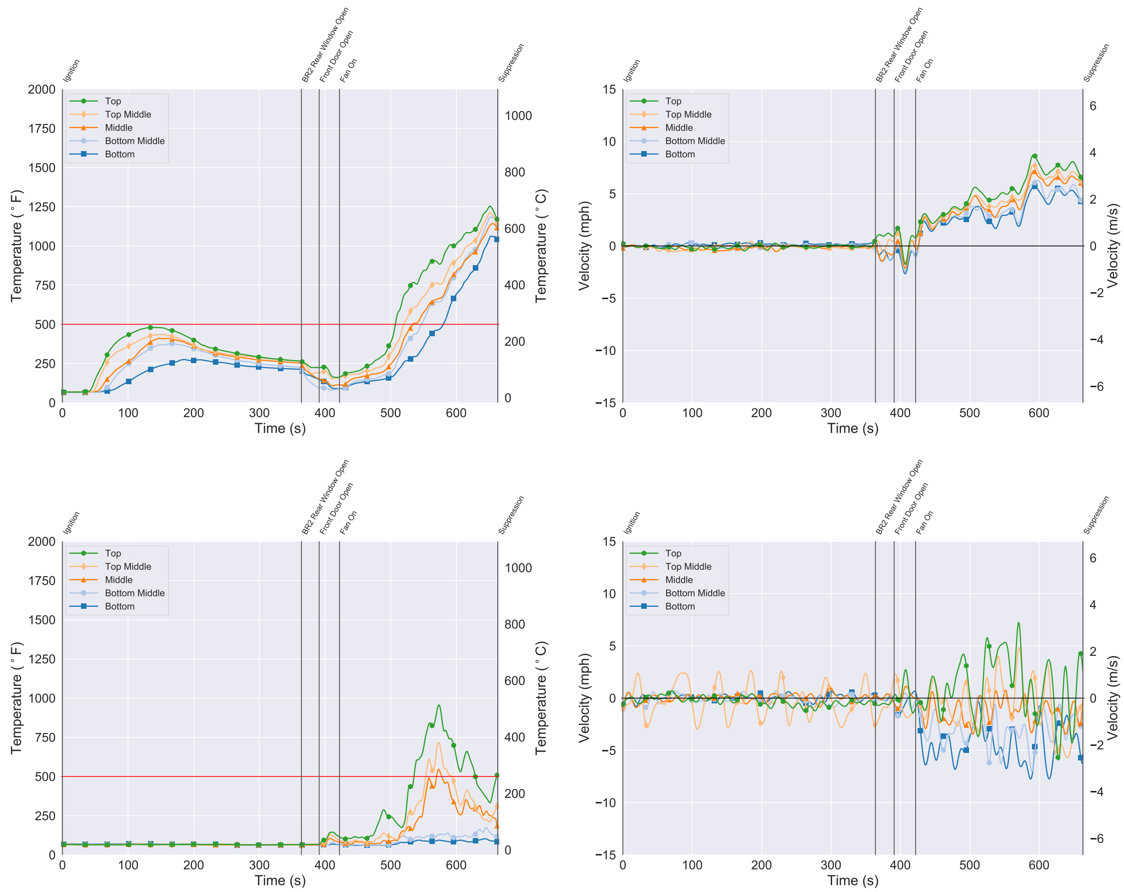

Figure C.35: Experiment 12 temperatures and gas velocities for the Bedroom 2 Window (top) and Front Door (bottom).

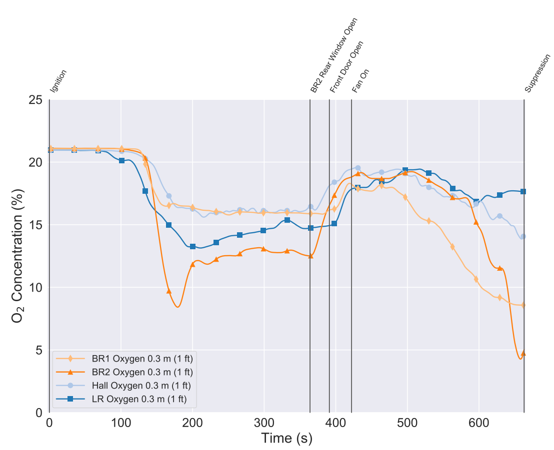

Figure C.36: Experiment 12 oxygen concentrations.