Impact of Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures

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UL Firefighter Safety Research Institute
Steve Kerber, Director

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List of Abbreviations

AF	Above floor
ATF	Bureau of Alcohol, Tobacco and Firearms
BC	Below ceiling
BDP	Bi-directional probe
CFI	Certified Fire Investigator
HGL	Hot gas layer
IAAI	International Association of Arson Investigators
NASFM	National Association of State Fire Marshals
NFPA	National Fire Protection Association
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
OSAC	Overseas Security Advisory Council
PUF	Polyurethane Foam
s	Second
TC	Thermocouple
UL FSRI	UL Firefighter Safety Research Institute

Acknowledgments

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To ensure the research results are of use to the fire investigation community, UL FSRI assembled a technical panel of national fire investigation experts that represent a range of forensic specialties in both the public, private, academic, and research sectors. The individuals below provided direction for the project by assisting in planning the experiments, witnessing the testing, and reviewing the results.

Fire Service Technical Panel

Name	Affiliation
Robert Byrnes	Fire Department City of New York (ret.)
Steve Carman	Carman & Associates Fire Investigation, Inc
Paul Claflin	Bureau of ATF, Fire Investigation & Arson Enforcement Division
Chris Connealy	Texas State Fire Marshal, TDI Deputy Insurance Commissioner
Richard Dyer	Dyer Fire Consulting
John Golder	Forensic Investigation and Consultation, LLC
Mark Goodson	Goodson Engineering
David Icove	University of Tennessee, Knoxville
Thomas Kane	Fire Department City of New York
John Lentini	Scientific Fire Analysis, LLC
Thomas Lichtenstein	UL LLC
Jeffrey Lyle	Chicago Fire Department
Kevin McGrattan	National Institute of Standards and Technology
Robert Pyzyna	Northbrook Fire Department

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In remembrance of Michael Murphy, Chicago Fire Department and Jaime Novak, St. Paul Fire Department.

Executive Summary

Knowledge of fire dynamics is critical for fire investigators to properly identify a fire's origin. Fire dynamics depend on the relationship of the fuel, heat, and ventilation during a fire event. A ventilation change as simple as a door left open by an occupant fleeing the fire, a window open remote from the fire, or a window that fails as a result of fire growth could greatly impact the fire damage inside the structure.

During the past decade, research conducted for the purpose of examining firefighting tactics has brought focus to the impact that on-going changes in home construction materials, contents, size, and geometry have on a fire incident. Current residential structure fires are predominantly fueled by synthetic contents and commonly become ventilation-limited. How and where the fire receives oxygen, especially with a ventilation-limited fire, impacts the fire growth and subsequent fire damage patterns.

A review of the state of forensic science in the United States was published in 2009. The report, entitled *Strengthening Forensic Science in the United States: A Path Forward*, by the U.S. National Academy of Sciences, indicated that '...more research is needed on the natural variability of burn patterns and damage characteristics...'. The NIJ supported Fire and Arson Investigation Technology Working Group developed a list of research needs to support the operational requirements of fire investigations. The research needs identified included: 1) understanding of the effects of ventilation on fire damage and patterns; 2) repeatability and reproducibility of test measurements of large-scale structure fires, and 3) development of materials property data for accurate computer model inputs.

Objectives

The goal of this study was to improve the capabilities of the fire investigation community by adding to the knowledge base and transferring the findings as widely as possible in order to "get the science to the street." The primary objectives of this series of experiments as presented in this report include:

1. To examine how differences in ventilation to full-scale structure fires result in changes to the fire damage and fire patterns within the structure.
2. To measure the fire environment within the structures and compare the data with the fire damage in the structures.
3. To document the repeatability or lack thereof of the fire conditions and fire patterns within a structure based on the available ventilation.
4. To provide a discussion of basic fire dynamics in structures, specifically with regard to the impact of ventilation on the resulting fire patterns.

Technical Approach

To address the needs listed above, Underwriters Laboratories Inc. Firefighter Safety Research Institute (UL FSRI) conducted a study to examine how ventilation impacts fire damage patterns in single family homes. The test structures included a traditional 111 m^2 (1200 ft^2) single story ranch style structure (Figure 1) and a 297 m^2 (3200 ft^2) two story colonial style structure. The two story colonial had a contemporary open floor plan design with a two-story family room and open foyer (Figures 2 and 3). The experiments were planned with the assistance of a technical panel that included members of ATF, IAAI, NAFI, NASFM, NIST, NIST OSAC, and NFPA 921.

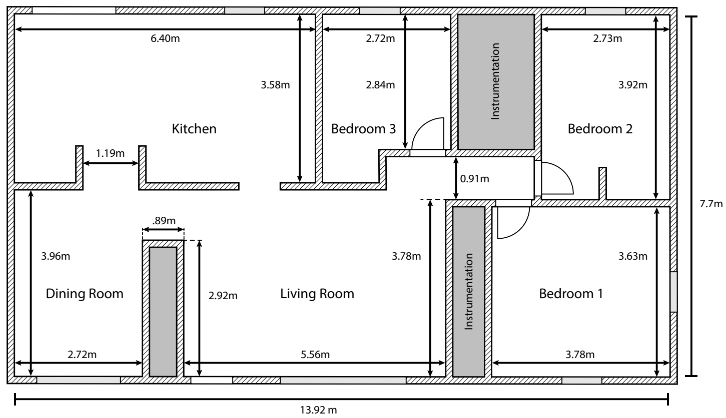


Figure 1: Plan-view dimensioned drawing of the single story structure.

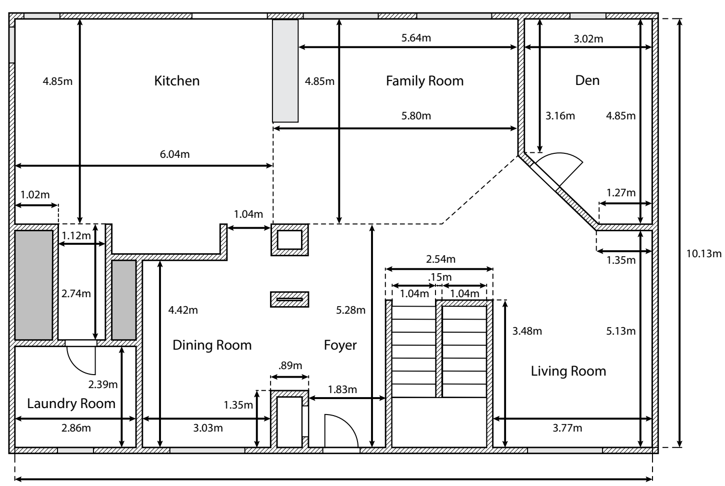


Figure 2: Plan-view dimensioned drawing of the first floor of the two story structure.

The test scenarios ranged from fires in the structures with no exterior ventilation to room fires with flow paths that connected the fires with remote intake and exhaust vents. In the single story structure, two replicate fires were conducted for each room of origin and each ventilation condition. Rooms of fire origin included the living room, bedroom, and kitchen. In the two story structure, the focus was on varying the flow paths to examine the change in fire behavior and the resulting

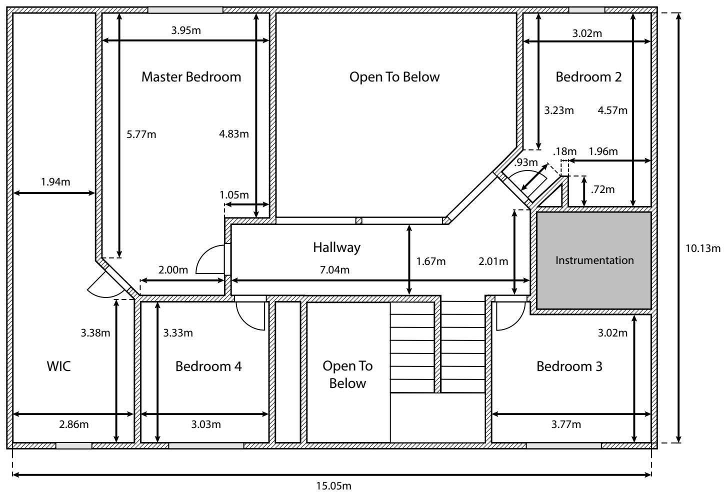


Figure 3: Plan-view dimensioned drawing of the second floor of the two story structure.

damage. Family room fires were conducted with five different ventilation configurations. In addition, two experiments were conducted in small rooms in the two story structure. The laundry room fire had a remote exterior vent, and the den fire had a vent adjacent to the fire as well as a remote vent. In the exterior vent experiments, the baseline vent was an open front door. Any additional vents were windows. After each fire scene was photographed, the interior finish and furnishings were replaced in affected areas of the structure to prepare for the next experiment.

Instrumentation was installed to measure gas temperature, gas pressure, and gas movement within the structures. In addition, oxygen sensors were installed to determine when a sufficient level of oxygen was available for flaming combustion. Standard video and firefighting thermal imaging cameras were also installed inside the structures to capture information about the fire dynamics of the experiments. Video cameras were also positioned outside the structures to monitor the flow of smoke, flames, and air at the exterior vents. Although the number of data channels used varied based on the ventilation configuration, the single story had 140 instruments installed and the two story had 195 instruments installed. During the experiments, each channel was scanned every second and recorded on a computerized data acquisition system.

Each of the fires were started from a repeatable, small flaming source. The fires were allowed to develop until they self-extinguished due to a lack of oxygen or until the fire transitioned through flashover. The times each fire burned post-flashover varied from less than one minute in experiments in which the fire self-extinguished due to a lack of oxygen, to seven minutes in which the fire could sustain post-flashover burning. The goal was to have patterns remaining on the ceiling, walls, and floors post-test. In total, 13 experiments were conducted in the single story structure, and eight experiments were conducted in the two story structure. All of the experiments were conducted at UL's Large Fire Laboratory in Northbrook, IL.

Example of Repeatability Comparison

After the experiments, the fire scenes were photographed, data was plotted, and videos were reviewed. The numerical and visual field data were compared between the experiments to examine the repeatability of replicate fire experiments and examine the correlation of the change in fire damage relative to the change in ventilation.

The replicate ranch experiments demonstrated repeatability in fire behavior in comparing both of the numerical data trends and the fire damage observations. An example of the comparison of two living room experiments with the open front door as a vent to the exterior is provided below. One of the fundamental concepts demonstrated by these experiments is the relationship between oxygen consumption and the generation of heat.

Experiments 3 and 4 in the single story had all of the exterior doors and windows closed except for the open front door. The sofa fire grew to the point of generating flashover conditions within a portion of the living room. The flashover was supported by oxygen contained within the structure and from air flow through the front door. Post-flashover, the flaming combustion was sustained by the inflow of air through the doorway, and the temperatures throughout the structure remained elevated until suppression.

Figures 4 and 5 provide a graphic representation of the flow paths within the ranch structure. Figure 6.10 shows the flow of hot gases (see red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure open to the living room. As the hotter, higher pressure fire gases flowed into other rooms, like the kitchen, dining room, bedroom 2, or out the front door, the fresh air (see green arrows) in those rooms was displaced toward the area of origin. This represents the availability of oxygen needed for flashover. Post-flashover, the measurable air flow within the structure was minimal. The air entering through the front door flowed toward the seat of the fire which had moved from the area of origin toward the front door. The remainder of flow movement within the structure was the circulation of combustion products, as represented by the predominant red arrows in Figure 5. Bedrooms 1 and 3 were closed and were not part of the flow paths.

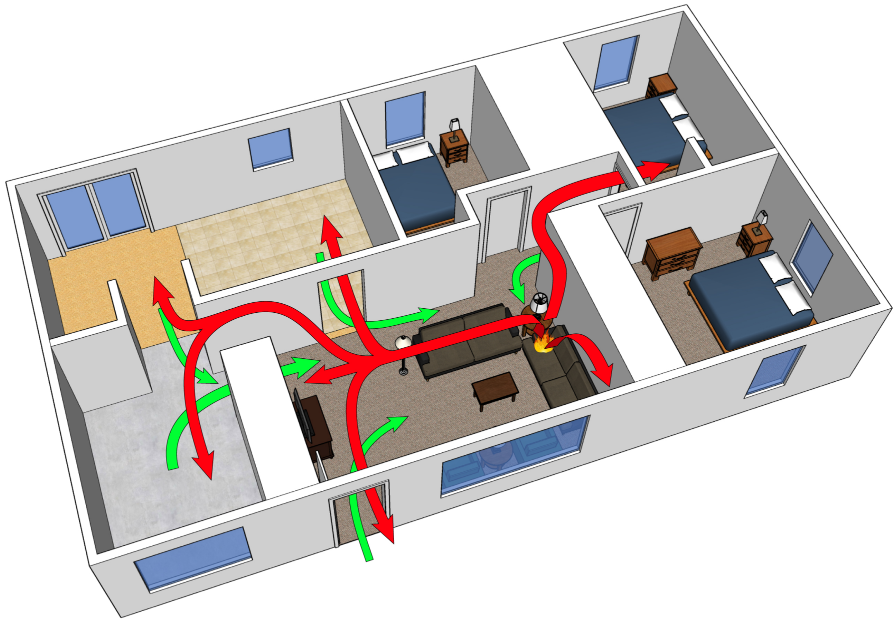


Figure 4: Drawing of the pre-flashover flows within the ranch structure, with a living room fire and open front door.

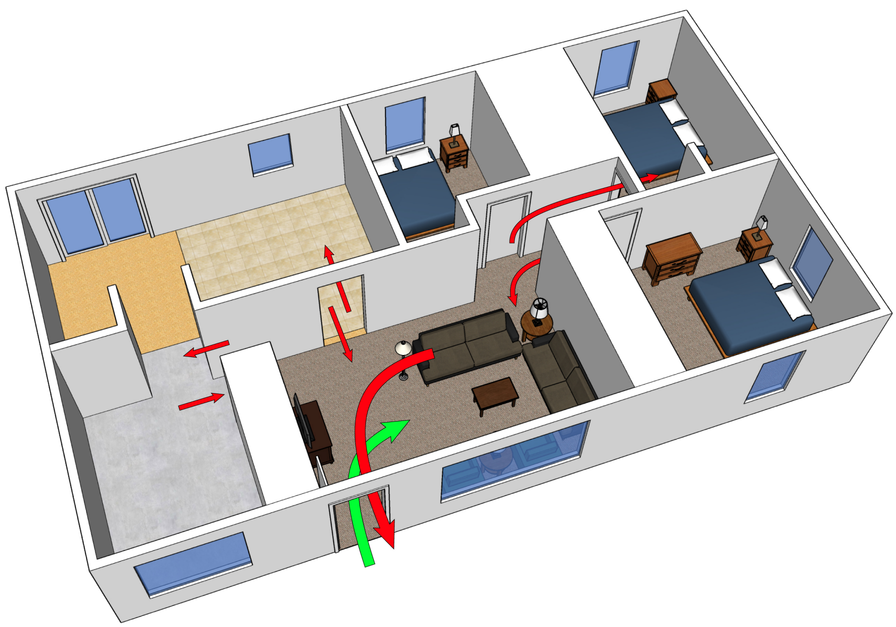
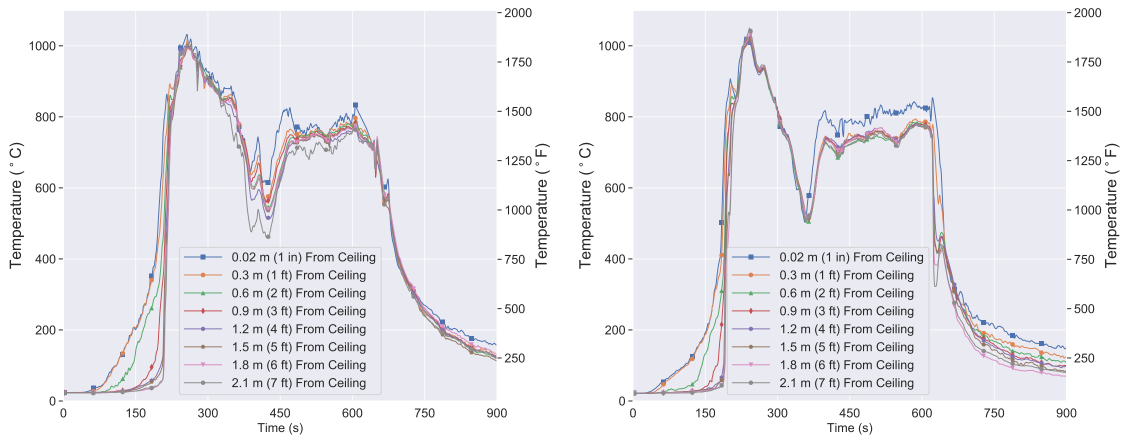


Figure 5: Drawing of the post-flashover flows within the ranch structure, with a living room fire and open front door.

The temperature time histories of the living room fires were similar in magnitude as shown in Figure 6. The growth rate, time to flashover, and post-flashover behavior were similar for both experiments. Experiment 4 showed a sharper decay, due to more efficient suppression actions.

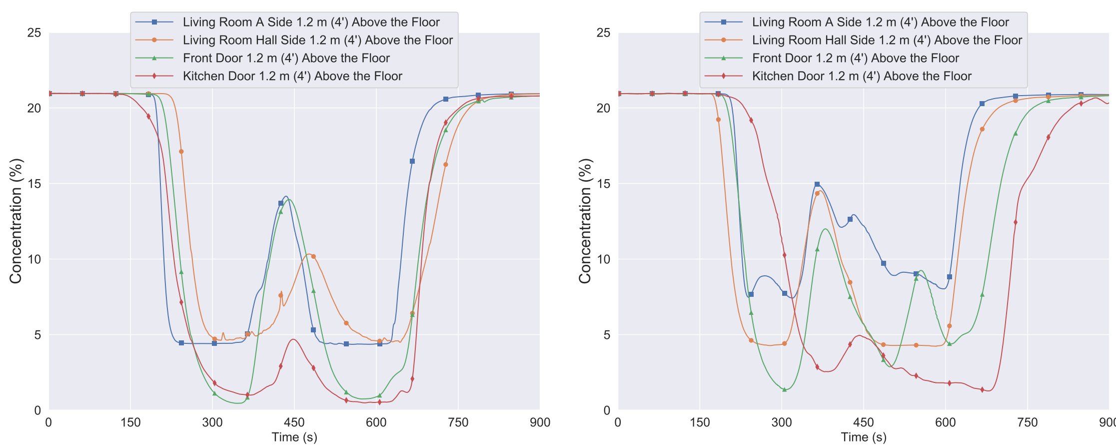


(a) Experiment 3

(b) Experiment 4

Figure 6: Comparison of open door, living room fire temperatures.

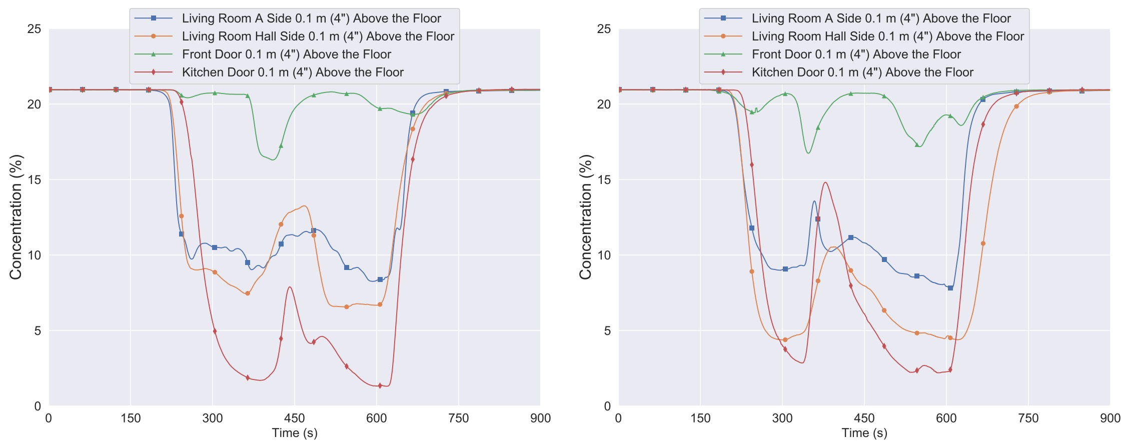
In both experiments, post-flashover, the oxygen levels measured at 1.2 m above the floor at locations bounding the living room decreased to 5%–8% as shown in Figure 7, recovered to approximately 15% as the fire decayed, and again dropped to 5%–8% as the fire recovered. The oxygen levels measured at 0.1 m above the floor in similar locations, Figure 8, showed a similar trend for the living room and kitchen: There was a decay to between 5%–10%, a recovery, and then a second decay before a full recovery to ambient levels following suppression. The oxygen sampling position near the floor by the front door did not see as significant of decay in either experiment as the door fluctuated between exhaust and intake. Although each of the oxygen concentration values between are not exact matches, the trends are similar, and the relationship between oxygen values and the increase and decrease in temperatures in the living room are consistent.



(a) Experiment 3

(b) Experiment 4

Figure 7: Comparison of open door oxygen concentrations at 1.2 m above the floor.



(a) Experiment 3

(b) Experiment 4

Figure 8: Comparison of open door oxygen concentrations at 0.1 m above the floor.

Fire Damage Comparisons

Figures 9 and 12 show the post fire suppression photographs of the living rooms that burned with the front door open. Both rooms burned for approximately seven minutes post-flashover.

The first two sets of photographs show the area of origin (see Figures 9 and 10). These two living rooms have many similarities. The wall behind the ignition sofa and the floor area under the sofa have fire damage patterns above and below the outline of the sofa that frame the point of origin. Both walls have a vertical damage pattern starting above the back of the sofa and continuing toward the ceiling.

Both ceilings have had most of face paper of the gypsum board burned off over the full length and width of the living room. The carpet and padding had been burned with the exception of some small protected areas, such as under a solid object like the base of the floor lamp or the TV stand. The sub-floor was charred from the ignition wall to the front door and from the second sofa to the front wall. The horizontal line of demarcation on the left wall was approximately 0.75 m (2.5 ft) above the floor in both experiments.

All of the upholstered furniture had been burned to the wood frame, which was charred. There was no directionality to the fire damage of the furniture, as there had been in the two living room experiments with all of the exterior vents closed. All four sides of the wood moulding surrounding the living room window opening was charred. The exposed moulding around the front door was also charred. The moulding on the hinge side of the door had less damage along the lower half of the door than the rest of the door moulding. The baseboard moulding along the floor under the window was charred along its length except where it was protected by a chair or toward the corner near the ignition sofa. The baseboard moulding along the left wall was undamaged, and the baseboard on the ignition wall and the TV wall only had charring in the area behind the sofa or behind the TV stand.

(a) Experiment 3

(b) Experiment 4

Figure 9: Post-suppression comparison of living room area of origin, with open door.

(a) Experiment 3

(b) Experiment 4

Figure 10: Post-overhaul comparison of living room area of origin, with open door.

Figures 11 and 12 show the area adjacent to the front door. Both walls show a dark pattern on the wall in the area of the TV stand. There is an area in the center of each pattern that has additional burn damage, some portions of it clean burned. On the right side of each of the patterns is a dark plume mark that sweeps over and up the right side. This collection of damage was likely caused by the intake air from the door, which enabled the TV stand to burn later into the fire event, resulting in a clean burn in the middle of a pre-flashover soot pattern, and the flow of the intake air caused the combustion products from the burning TV stand to flow toward the inside of the house. If the outward plume pattern was caused by an obstruction and not impacted by the ventilation, two equal plumes on both sides of the TV stand would be expected.

(a) Experiment 3 (b) Experiment 4

Figure 11: Post-suppression comparison of living room wall opposite the area of origin and adjacent to front door with open door.

(a) Experiment 3 (b) Experiment 4

Figure 12: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with open door.

Based on the observations, and looking at the various surfaces and target fuel material that was positioned around the living room, there were no major differences. Basically, both rooms were consistent with post-flashover burning and had similar, not identical, but similar damage patterns.

Example of the Impact of Ventilation Comparison

In the previous section, the repeatability of a pair of fire experiments with the same ventilation configuration was compared. In this example, the living room fires, Experiments 1 and 2 with no exterior vents and Experiments 3 and 4 with the front door open, were compared.

In the experiments in the closed structures, the living room fires were ignited, flashed over, and self-extinguished in less than five minutes. The post-flashover burn time was 30 s or less, due to oxygen depletion. In the living room fires with the front door open, the supply of oxygen laden fresh air allowed the fires to continue to burn until it became fuel depleted. These fires were extinguished by a hose stream prior to running out of fuel. The time from ignition to the start of suppression was approximately 10 minutes. Both experiments burned for approximately seven minutes post-flashover.

Figures 13 and 14 show the post fire suppression photographs of the living rooms that burned with no open exterior vent and with front door open, respectively. The difference in the extent of the fire damage is clear. The open door provided an exhaust vent for oxygen depleted combustion products and an intake vent for air. The continued supply of air supported combustion for a longer period of time. During that time, the combustion zone moved from the area of origin toward the open front door, and then later in the experiment the fire began to move back toward the area of origin.

(a) Experiment 1 (b) Experiment 2

Figure 13: Post-suppression comparison of living room area of origin, with closed door.

(a) Experiment 3 (b) Experiment 4

Figure 14: Post-suppression comparison of living room area of origin, with open door.

In the open door experiments, when the combustion moved toward the front door, the TV stand was ignited. The difference in the fire patterns created on the wall near the front door depending on whether the door was opened or closed appears in Figures 15 and 16. The ventilation impacted fire damage patterns generated by the burning dresser next to door with an air velocity of 1.4 m/s (3 mph) entering the lower portion of the open doorway (see Figure 16).

(a) Experiment 1 (b) Experiment 2

Figure 15: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with closed door.

(a) Experiment 3 (b) Experiment 4

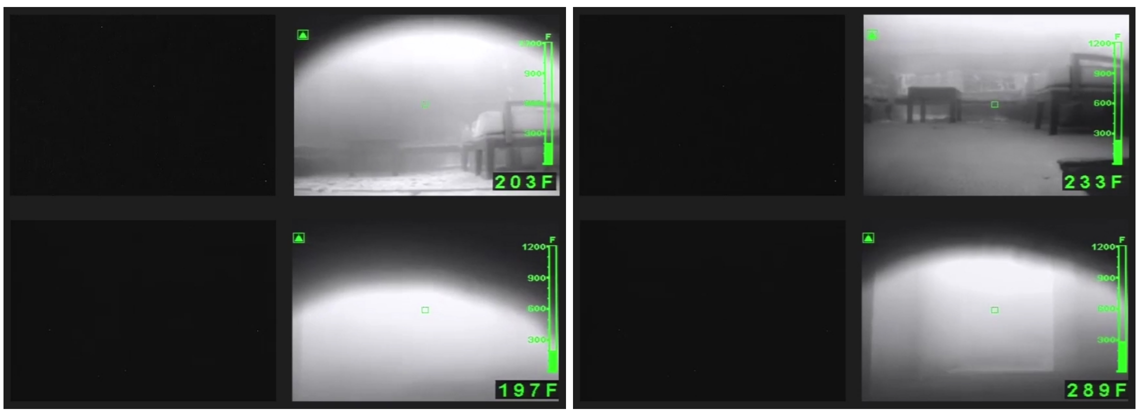
Figure 16: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with open door.

For flaming fire to exist, it needs fuel, heat and oxygen in order to support the sustained chemical reaction. The mixture of fuel and oxygen must be in an appropriate proportion in order to burn. Too much fuel and the mixture is too rich to ignite. Too much oxygen and the mixture may be too lean to ignite. The ideal mixture of air to fuel is referred to as a stoichiometric mixture. This means the air has enough oxygen to burn all of the fuel with no air left over. As an example, the stoichiometric air-fuel ratio for gasoline is 14.7 to 1. The review of the experiments in this study, and previous studies, demonstrate that residential compartment fires generate a fuel rich environment.

The next set of figures have images from video cameras and thermal imaging cameras that were installed in the structures side by side. The thermal imager provided a sense of where the heat was in the structure at a given time even if the video camera view was obscured by smoke. This also gives us a sense of where the air-fuel mixture was in range for combustion and generating heat.

Pairs of video and infrared images are from two different positions. The two upper views in each set of images are from cameras installed between the front door and the TV stand and aimed toward the area of origin. The lower two views in each set of images are from cameras installed in the dining room and aimed toward the living room. The center of the thermal image view was approximately 1 m (3 ft) to the left of the point of fire origin.

All images were taken at 300 s after ignition. The images in Figure 17 show that in Experiments 1 and 2 (exterior vents closed), the fire had depleted the oxygen levels within the structure such that the flames self-extinguished shortly after flashover. The images in Figure 18 were from Experiments 3 and 4, which had the front door open. The air flow through the open door enabled the fire to continue to burn post-flashover. However, at this point, the fire was only burning near the open front door where the hot fuel gases could mix with oxygen entering the door (see upper images). At the same time, the gas-phase combustion near the area of origin had stopped due to a lack of oxygen (see lower images). In both open door experiments, shortly after flashover the estimated wall temperature adjacent to the point of ignition decreased to less than 200 °C (400 °F).



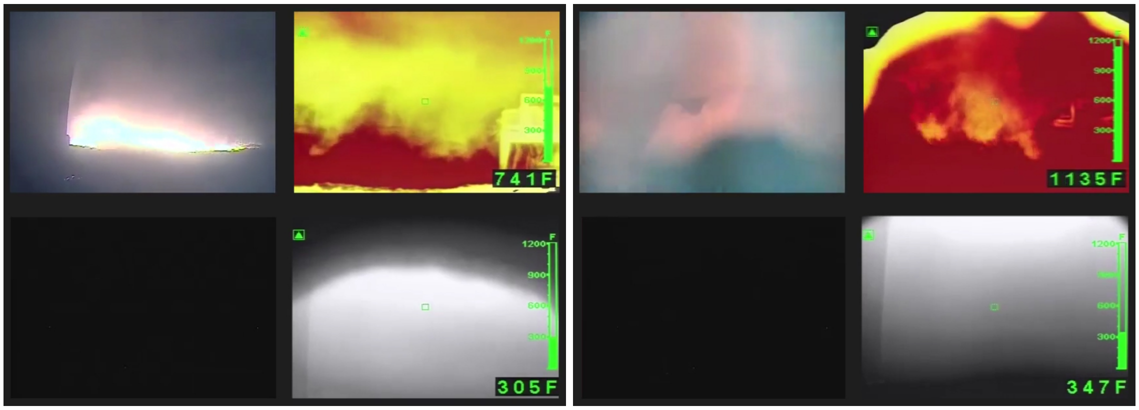
(a) Experiment 1

(b) Experiment 2

Figure 17: Pairs of video and infrared images from two views of the living room for Experiments 1 and 2 at 300 s after ignition, closed door. The two upper views in each set of images are from cameras near the front door and looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, with the center of the image view approximately 1 m to the left of the area of origin.

Another way to examine the impact ventilation had on the fire is to look at images of the exterior of the structures. Again, these images were captured at 300 s after ignition for direct comparison with the thermal images above.

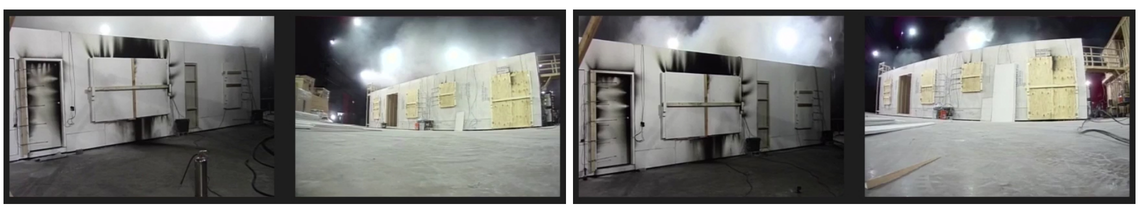
Figure 19 shows the lack of smoke flow out of the structure at this time. The soot marks on the front door and above and below the front window shutters are evidence that as the fire was growing, the gas pressure inside the structure was sufficient to force smoke around the edges of the closed vents. In the case of the front door, we have evidence the smoke was all the way down to the floor when it was being forced out close to the bottom of the door. By 300 s, after ignition the fires had self extinguished due to a lack of oxygen. The gas temperatures had decreased, and the pressure inside the structure was less then the pressure outside of the structure, so the smoke stopped pushing out.



(a) Experiment 3 (b) Experiment 4

Figure 18: Pairs of video and infrared images from two views of the living room for Experiments 3 and 4 at 300 s after ignition, open door. The two upper views in each set of images are from cameras near the front door and looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, with the center of the image view approximately 1 m to the left of the area of origin.

Experiments 3 and 4 had the front door open from the time of ignition. Images of the front and rear of the exterior of the structure with the open door appear in Figure 20. In both experiments, the fire can be seen burning in close proximity to the open door. The open door acted as a bidirectional vent having both an air intake and an exhaust.



(a) Experiment 1 (b) Experiment 2

Figure 19: Images of the exterior of the structure for Experiments 1 and 2 at 300 s after ignition, closed door. The left view of each pair of images is the front side. The right view of each image pair is of the back side.

Findings

Review of the results from the 21 full-scale fire experiments yielded the following:

1. Increasing the ventilation available to the fire resulted in additional burn time, additional fire growth, and a larger area of fire damage within the structures. These changes are consistent with fire dynamics based assessments and were repeatable.

(a) Experiment 3 (b) Experiment 4

Figure 20: Images of the exterior of the structure for Experiments 1 and 2 at 300 s after ignition, open door. The left view of each pair of images is the front side. The right view of each image pair is of the back side.

2. Fire patterns within the room of fire origin led to the area of origin when the ventilation of the structure was considered.
3. Fire patterns generated pre-flashover persisted post-flashover if the ventilation points were remote from the area of origin. Pre-flashover fire damage patterns near open exterior vents were more difficult to distinguish from post-flashover damage or were eliminated completely.
4. The location of the ventilation relative to the origin of the fire changed the location and extent of the fire damage within the structures as the ventilation configuration affected the availability of the oxygen to the fire.

Outputs

This report, the time histories of the data, and the videos from this study (available on-line from ulfirefightersafety.org) provide foundational documentation for understanding ventilation-controlled fires and the resulting fire damage patterns. This study supports the understanding of separate and distinct fire patterns generated pre-flashover and post-flashover by ventilation-controlled burning conditions in a structure.

In addition to this report, other means of sharing the knowledge from this study will be leveraged to optimize the use of this information by the fire investigation community. To that end, UL FSRI will perform the following actions:

1. Develop and host a freely available website that will serve as a repository for the information from this study, including the final report, videos of the experiment, and interactive floor plans with the data from the experiments. This repository will be available from the UL FSRI website, ulfirefightersafety.org.
2. Share the resources of this study with the NFPA Technical Committee on Fire Investigations and the NFPA Technical Committee on Fire Investigator Professional Qualifications.
3. Assist with the revision and development of the Fire Investigator Training Courses given at FEMA's National Fire Academy.

4. Participate on the revision of the International Fire Service Training Association's Fire Investigator 3rd edition training manual.

5. Assist with the creation of a new IAAI CFITrainer.net® on-line Module, *Fire Flow Analysis*.

6. Assist with the production and support of the UL XPLORLABS on-line learning module, Fire Forensics: Claims and Evidence (available from https://ulxplorlabs.org/fire-forensics-claims-and-evidence/).

1 Background

Fire investigation is part of the community risk reduction system that generates data to enable the mitigation of fire losses. The investigation of fires provides a means to identify the cause of the fire in order to develop a knowledge base that could enable the elimination of that cause, and thus further reduce the losses from fires. Data such as the room of fire origin, the first item ignited, and ultimately the cause of the fire is information critical to understanding and reducing the number of fires. For example, the identification of products involved in ignitions due to a design flaw in many cases result in the U.S. Consumer Product Safety Commission or a manufacturer issuing a product recall. There are two notable and recent examples of this process. As result of reports of fire and overheating incidents, 1.9 million Samsung Galaxy Note7 smartphones and 0.5 million hoverboards were recalled in 2016 [1,2].

In some cases, the fire investigation determines the fire was intentionally set. An intentional fire, as defined in the National Fire Incident Reporting System (NFIRS), are those fires that are deliberately set and include fires that result from deliberate misuse of a heat source, fires of an incendiary nature (arson), as well as controlled burn fires, such as crop clearing, that required fire service intervention [3]. An incendiary fire, as defined by the National Fire Protection Association (NFPA) Guide for Fire & Explosion Investigations, commonly referred to as NFPA 921, is “a fire that is deliberately set with the intent to cause a fire to occur in an area where the fire should not be” [4].

According to the NFPA, there were approximately 261,000 intentionally set fires each year from 2010 through 2014 in the United States. The average annual loss totals from intentionally set fires were approximately 440 civilian deaths and 1,310 civilian injuries. More than $1 billion dollars (U.S.) was lost per year due to direct property damage. Structure fires represent less than 20% of intentionally set fires. However, fires involving structures account for more than 84% of the civilian deaths, injuries, and property loss from all intentional fires. Approximately two-thirds of the intentional structure fires occurred in occupied and operating residential occupancies. As a result, 97% of the civilian deaths and 85% of the civilian injuries attributed to intentional fires occurred in residential occupancies [5]. Therefore the investigation of residential structure fires is of great interest.

1.1 The Use of Fire Patterns in Fire Investigation

Fires are investigated in order to determine their origin and cause. In cases of arson, there is an additional effort to determine who was responsible for setting the fire. This investigation process should follow the scientific method, as documented in NFPA 921 [4]. There are numerous textbooks on the subject of conducting a fire investigation [6–11]. The NFPA guide and the texts provide information how to collect data from the scene, analyze the data, and develop a hypothesis about the fire.

Patterns produced by the fire are, in many cases, a significant portion of the data collected and are analyzed at the scene to determine the area of origin. One of the basic methods of documenting the fire scene is to photograph fire patterns. As noted by Icove, DeHaan, and Haynes, "the ability to document and interpret fire patterns accurately is essential to investigators reconstructing fire scenes" [9]. A fire pattern is defined in NFPA 921 as, "the visible or measurable physical change, or identifiable shapes, formed by a fire effect or group of fire effects" [4].

DeHaan [12] categorizes the fire effects that form patterns as follows:

1. Surface deposits: no irreversible effect on surface
2. Surface thermal effects: physical change such as discoloration or melting
3. Charring: evidence of surface burning
4. Penetration: charring below the surface
5. Consumption: loss of surface material, charring throughout

Lentini points out that most fire patterns are generated and later observed on two-dimensional surfaces at the place where those surfaces intersect with the three-dimensional fire. Various types of fire patterns, such as V-shaped, hour-glass, and inverted cone, have come from common observation at actual fire scenes [10]. The observations are typically qualitative in nature.

Previous fire pattern research by the National Institute of Justice (NIJ), the National Institute of Standards and Technology (NIST), and the United States Fire Administration (USFA) has shown that fire patterns provide data useful for the determination of fire origin. The reports noted the impact of ventilation on the development of burn patterns [13, 14]. A large number of other factors affect the formation of these patterns: burn time, heat release rate of the fire source, fire exposure, target fuel composition, adjacent fuel(s), and compartmentalization, to name a few. Given the limited number of experiments in the literature and the large number of variables, it has been difficult to identify a cause and effect relationship between fire scenarios and the resulting patterns, based solely on the research.

Fire pattern interpretation and analysis is a critical step in most fire investigations. Gorbett recently conducted a review of fire pattern research that has been conducted over the past 80 years. The review points out many gaps, especially with how fire patterns are used to determine the area of origin. A key limitation is the assumption, by many of the researchers and text authors, that investigators are able to visibly assess varying degrees of fire damage and then determine the area of origin [15]. Studies have shown that investigators have not been able to use only the location of the fire patterns as means of reliably determining area of origin. Some amount of analysis and fire dynamics knowledge is required [16, 17].

1.2 Fire Investigation Under Review

The fire investigation community recognized a need to improve the science and practice of fire investigation. One of the manifestations of the efforts to improve the practice was the development of NFPA 921, *Guide for Fire and Explosion Investigations* [4]. The first edition of NFPA 921 was issued in 1992. As provided by the document scope, it "is designed to assist individuals who are charged with the responsibility of investigating and analyzing fire and explosion incidents and rendering opinions as to the origin, cause, responsibility, or prevention of such incidents, and the damage and injuries which arise from such incidents." The document's purpose includes the goal to be "a model for the advancement and practice of fire and explosion investigation, fire science, and methodology." However, NFPA 921 can only incorporate the fire science and research results that have been produced. Although NFPA 921 is a guide, as opposed to a standard, it is considered the *standard of care* for the fire investigation community in countries that recognize and use NFPA standards and guides.

As a result of the review of several arson cases, most notably the cases of Ernest Ray Willis and Cameron Todd Willingham, the practice of fire investigation as a forensic science was called into question. Beyler conducted a review of both cases for the Texas Forensic Science Commission [18]. Both fires occurred prior to the release of NFPA 921 in 1992. The Beyler analysis, issued in August of 2009, concluded that the investigations of both cases "did not comport with either the modern standard of care expressed by NFPA 921, or the standard of care expressed by fire investigation texts and papers in the period 1980–1992." The fire investigators had a poor understanding of science, and their findings of arson could not be sustained [18].

Another landmark document regarding the state of forensic science in the United States was published in 2009. The 328 page report, entitled *Strengthening Forensic Science in the United States: A Path Forward*, by the U.S. National Academy of Sciences, reviewed 13 different forensic science disciplines including biological evidence, friction ridge patterns, tool mark and firearms identification, and analysis of explosives evidence and fire debris. The review of the analysis of explosives evidence and fire debris is covered in three pages of the report. The summary assessment of analysis of explosives evidence is positive, "the scientific foundations exist to support the analysis of explosions, because such analysis is based primarily on well-established chemistry" [19]. The complete summary assessment for fire analysis states:

> By contrast, much more research is needed on the natural variability of burn patterns and damage characteristics and how they are affected by the presence of various accelerants. Despite the paucity of research, some arson investigators continue to make determinations about whether or not a particular fire was set. However, according to testimony presented to the committee, many of the rules of thumb that were typically assumed to indicate that an accelerant was used (e.g., alligatoring of wood, specific char patterns) have been shown not to be true. Experiments should be designed to put arson investigations on a more solid scientific footing.

This study was in response to the assessment above, specifically regarding the natural variability of fire patterns. Further, several of the fire and arson investigation research issues identified by the NIJ supported Fire and Arson Investigation Technology Working Group Operational Requirements (December 2016) were incorporated into this project to some extent. Specifically these include: 1) understanding of the effects of ventilation on fire damage and patterns; 2) repeatability and reproducibility of test measurements of large-scale structure fires; and 3) development of materials property data for accurate computer model inputs [20].

1.3 Previous Structural Ventilation Research

During the past decade, research conducted for the purpose of examining firefighting tactics has brought focus to the impact that changes in home construction materials, contents, size, and geometry have on a fire incident. Current residential structure fires are predominantly fueled by synthetic contents and commonly become ventilation-limited. How and where the fire receives oxygen impacts the fire dynamics and subsequent fire patterns.

Over the past 50 years, changes in construction materials, construction methods, insulation, and furnishings have changed the means and the speed of fire growth within a structure. Both research experiments and investigations of Line of Duty Death (LODD) and Line of Duty Injury (LODI) have demonstrated the importance of understanding of how ventilation affects fire behavior. How, where, and when a fire receives oxygen greatly impacts the fire dynamics and the resulting thermal environment inside the structure.

In the 1950s, a wide range of synthetic materials called polymers became available for use in clothing, furniture, interior finish, and insulation. Today, the use of polyester, polystyrene, polyethylene, nylon, and polyurethane foam has become commonplace in homes, vehicles, and industry. Durability, comfort, and economics all play a role in the design and manufacturer of furnishings that people choose to buy. Flexible polyurethane foam is one of the most common materials used in upholstered furniture. Figures 1.1 and 1.2 provide a snapshot of the difference in fire development speed, fire size, and heat release rate between a sofa with cotton cushions and a sofa with polyurethane foam cushions.

Given the differences in fire development between a sofa with cotton padded cushions and a sofa with polyurethane cushions, it was not surprising the sofa made with foam plastic cushions had the potential to flashover a well-ventilated compartment in a short period of time. The paper, "Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes," examined this [21]. Kerber conducted a series of compartment fire experiments to examine the difference in time to flashover between a room furnished with legacy fuels and a room furnished with modern fuels. Legacy fuels meant furnishings made from wood, steel, and cotton. Modern fuels are characterized by polyurethane foam, polyester fiber and fabric, engineered wood, and plastics in many different forms. Each room was ignited by a small open flame from a candle on the sofa. The flashover times for the modern room averaged 235 s after ignition. Only two of the three legacy room fires resulted in flashover. The average flashover times for the two legacy rooms was 1,912 s after ignition. It took eight times longer for the cotton sofa to generate enough

Figure 1.1: Comparison of upholstered sofas: cotton versus polyurethane foam. Images recorded approximately 180 seconds after ignition.

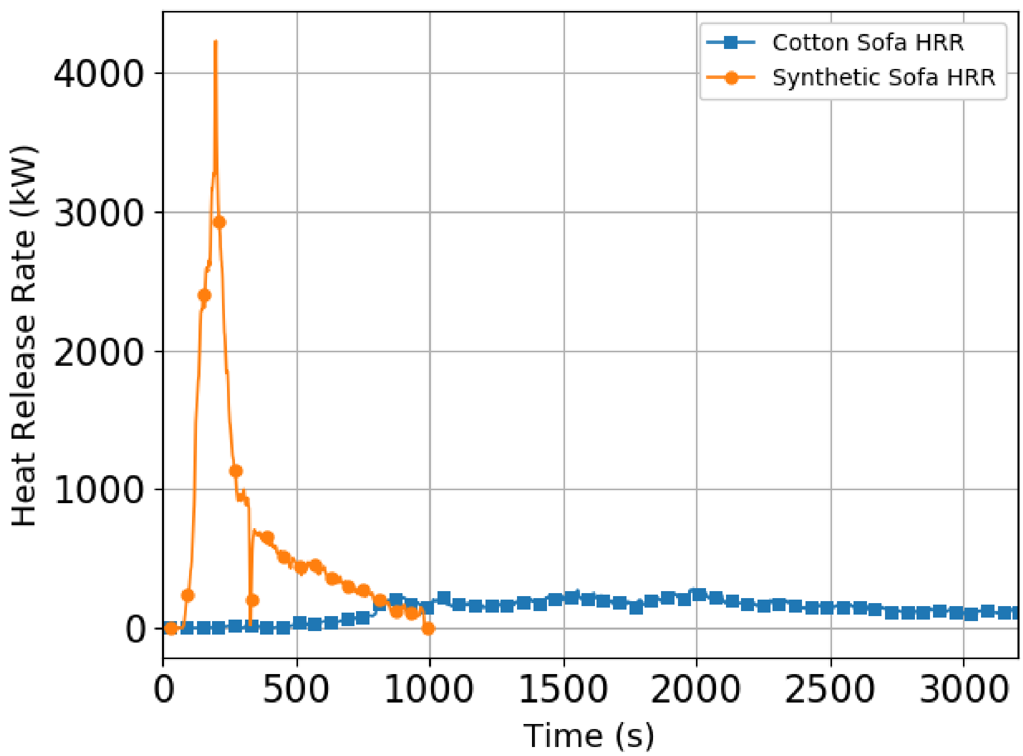
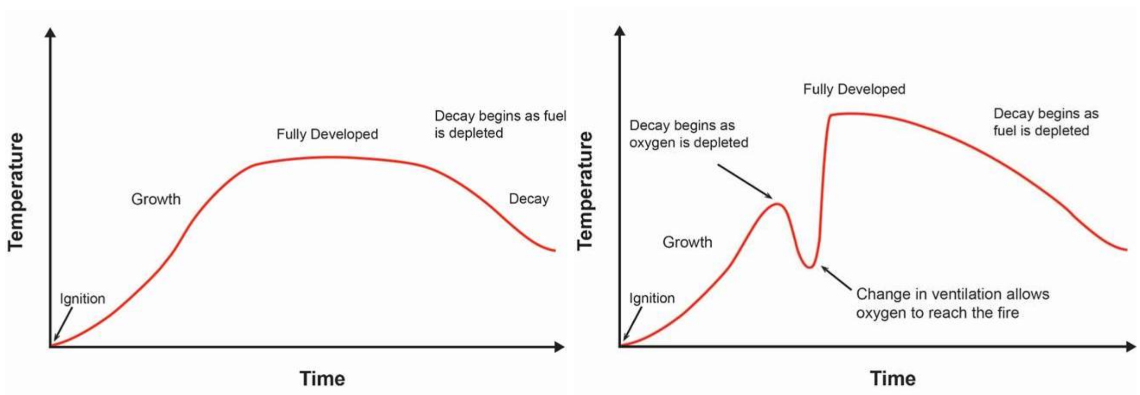


Figure 1.2: Comparison of upholstered sofas HRR: cotton versus polyurethane foam.

heat release rate to spread fire throughout the room [21].

Following the recognition of rapid flashover times, the UL Firefighter Safety Research Institute (FSRI) team examined the impact of the synthetic fuels by conducting several research studies in structures built in their laboratory to resemble a single story and a two story home [22, 23]. The results of the experiments demonstrated that ventilation limited fire conditions are likely to exist prior to fire department arrival and continued in the structures after venting, either horizontal or vertical, until suppression actions reduced the heat release rate of the fire. As the buildings were vented, oxygen entered the hot, fuel-rich, (ventilation limited) environment within the structure, which resulted in rapid (30 s to 120 s) increases in heat and gas velocities in portions of the structure.

The differences in the behavior of a ventilation-controlled fire appear in Figure 1.3. The curves shown are idealized representations of a fuel-controlled fire and a ventilation-controlled fire within a compartment or structure. The heat release rate of the fuel-controlled fire is limited by the amount of fuel burning at any given time, because in this scenario the fire has adequate oxygen available to support flaming combustion. In the ventilation-controlled case, the heat release rate of the fire is limited by the amount of oxygen available for combustion.



(a) Fuel controlled

(b) Ventilation controlled

Figure 1.3: Idealized fire curves: fuel versus ventilation controlled.

For the purposes of this fire pattern study, fire is considered to be a gas-phase chemical reaction that emits heat and light. In other words, the focus was on where flaming combustion can take place and generate fire damage. Solid phase combustion is not the focus of this study.

In the most basic terms, fire needs three basic components to exist: fuel, heat, and oxygen. If the fire investigator can determine where and when these three components are available to react and support combustion, they will have some ability to understand the movement of a fire through a structure. Cox demonstrates how investigators can conduct a pre-flashover and post-flashover assessment of fire damage in a structure based on the components of the fire triangle, in his origin matrix analysis method [24].

If a fire investigator is going to analyze a fire based on when and where the fuel, heat, and oxygen coexist, it is also important to understand how these components are transported through a compartment or structure. Typically the model of a compartment fire has been used to describe how the fire entrains air and consumes the oxygen in a chemical reaction, which results in the generation of heat and the loss and distribution of mass from the fuel. The heated gases generated by the fire are less dense than the surrounding air and rise to the ceiling of the compartment due to buoyancy. Once the gases impact the ceiling they turn and flow along the ceiling forming a ceiling jet (see Figure 1.4).

As the gases continue to heat, they expand and flow under the ceiling until the ceiling jet reaches the walls. As the walls constrain the hot gas flow, a hot gas layer begins to form in the compartment (see Figure 1.5). If the heat release rate of the fire is growing, the depth of the hot gas layer will continue to increase. However, if the door to the compartment is not opened and there is no other source of oxygen to continue the combustion process, the heat release rate from the fire will begin to decay and the fire may self-extinguish.

If the door to the fire compartment is opened, the hot gases will begin to flow out of the upper portion of the doorway and fresh air will flow into the lower portion of the doorway (see Figure 1.6). If the heat release rate of the fire is growing, the depth of the hot gas layer will continue to increase because the fire is generating more products of combustion than the open doorway can vent. If this situation continues, and fresh air is available for combustion through the lower portion of the open doorway, it is likely flashover will occur. Flashover is a transition from the two layer, hot gas over cool air, compartment fire model, to a single layer hot gas model with well mixed burning from the ceiling down to the floor. After this rapid transition it is likely the portion of the compartment remote from the open doorway will become oxygen depleted and the flaming combustion will cease.

This circulation of fresh air and smoke is referred to as the flow. A flow path is the volume in a building between at least one air intake and one hot gas exhaust that allows the movement of heat and smoke from the higher pressure zone within the fire area toward the lower pressure areas accessible via doorways, vented windows, stairways, and other openings. Based on varying building configurations, there may be several flow paths within a structure.

In the simple images of a fire in a single compartment, the flow path is contained within the fire room, with the upper portion of the doorway serving as the exhaust vent and the lower portion of the doorway serving as the intake vent. When an open vent serves both an intake and an exhaust, it can be referred to as a bidirectional vent. If the vent only has exhaust gases or intake air moving through it, it is called a unidirectional vent.

Under these flow conditions, the area favorable for combustion is near the open doorway, while flaming combustion in the area remote from the air supply may cease due to a lack of oxygen. Understanding the fire dynamics of this situation is very important for fire investigators, because if the fire was ignited remote from the air intake vent, early in the fire, thermal damage could be created at or near the site of ignition. If the fire continued to develop and transitioned from a fuel-controlled condition to a ventilation-controlled condition, it is possible that two discrete areas of fire damage might result. A fire investigator may interpret the pre-flashover damage in the area of origin and the post-flashover damage near the open doorway as two areas of origin and determine the fire to be intentional based on the separate fire patterns.

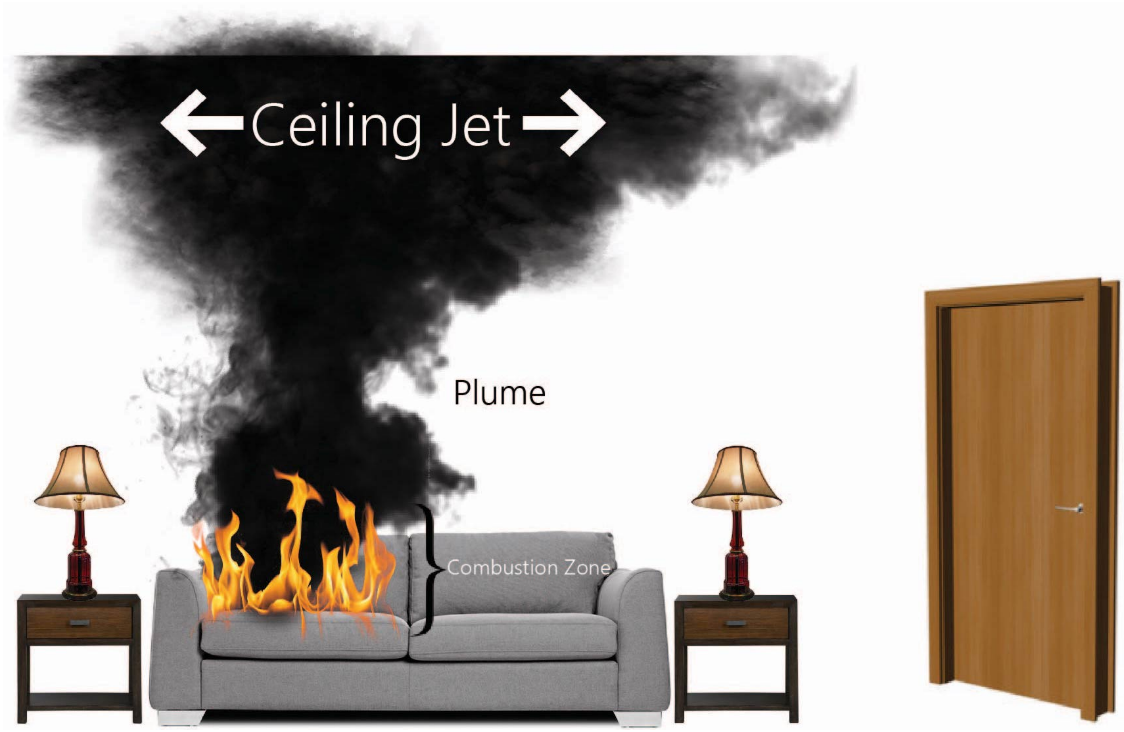


Figure 1.4: Drawing of the growth stage of a compartment fire, highlighting the thermal plume and the ceiling jet.

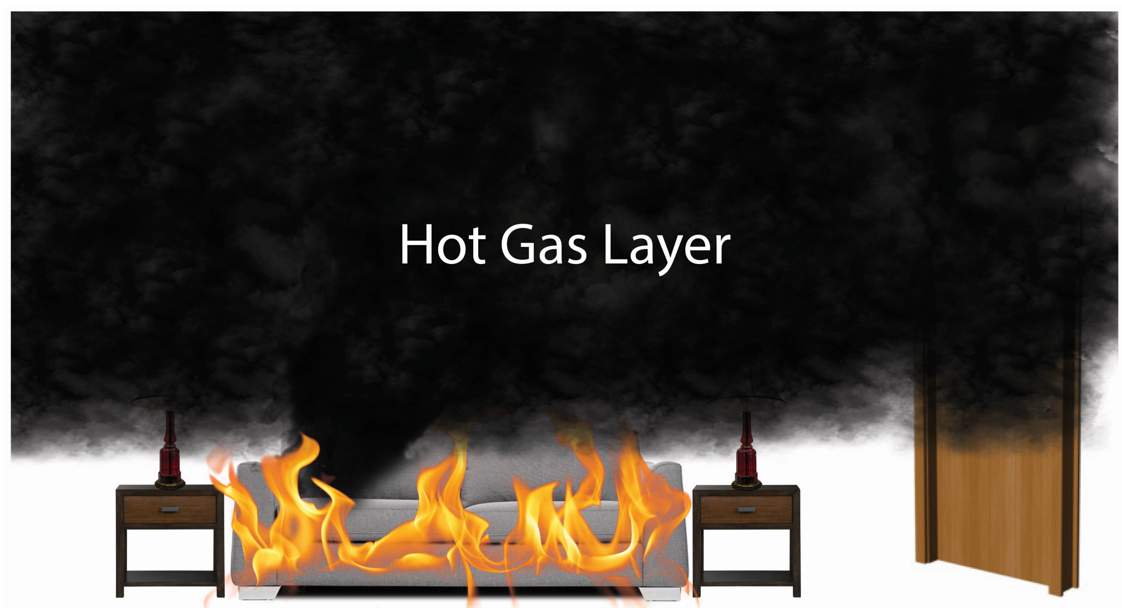


Figure 1.5: Drawing of the hot gas layer in a compartment fire.

More than a decade ago, Carman pointed out the need for further understanding of the impact of ventilation on fires [16]. In a number of training scenarios with one-room burn props, ATF instructors asked the students to examine the burn props at the beginning of the training class and

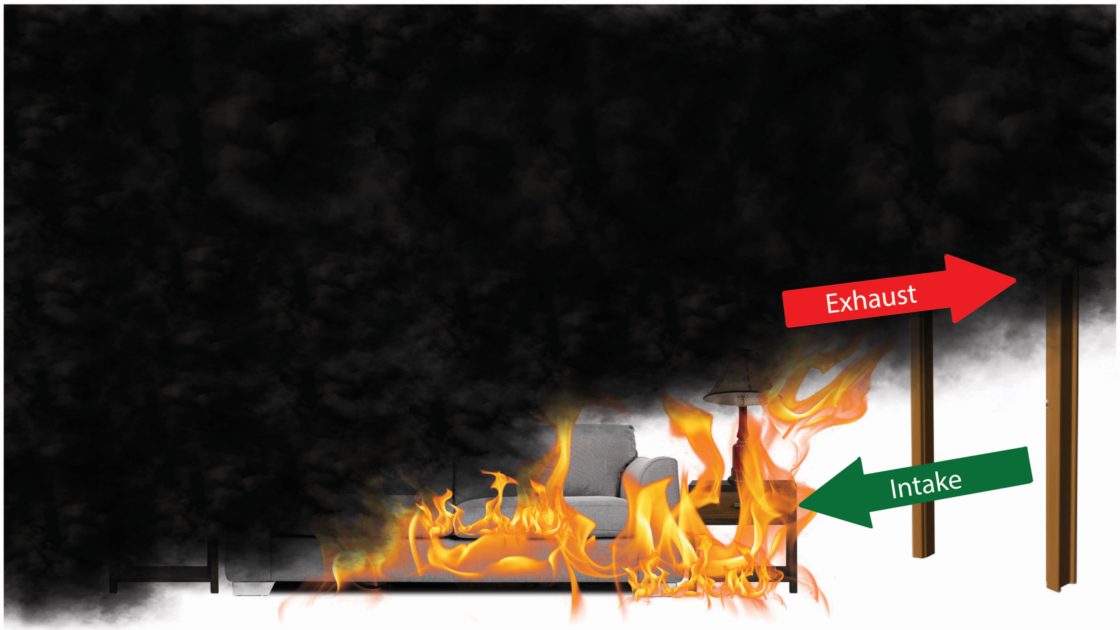


Figure 1.6: Drawing of the air and smoke flow in a compartment fire with an open doorway. The higher pressure hot gases flow out of the top of the doorway and cooler, denser fresh air flows into the lower portion of the doorway to supply oxygen to the fire.

identify the area of origin. The students had to make their determination based on the fire damage they could see. In these exercises, only a small percentage of the students were able to correctly identify the pre-flashover pattern as the area of origin. It is important to note that many of the students were not CFIs, they were only allowed to look at the patterns, and they were not allowed to work the scene, so the findings of the informal assessment may not be a true assessment of the capabilities of fire investigators across the nation. But the exercise did point out the importance of understanding and applying fire dynamics when analyzing fire patterns to determine an area of origin.

Working with the National Fire Academy at the U.S. Fire Administration, Campenelle and Avato of ATF participated in hundreds of fire investigation training fires over a five year period and documented fire damage in the area of origin, remote from the air intake, that were observable post-flashover [25]. The fires were typically conducted in a single room with a door and window to the outside. The fires used in the study had a point of origin against a wall, next to a sofa or bed, and remote from the door or window vents. The fires were allowed to burn post-flashover for two minutes or less. The review of these fires showed that the fire pattern at the point of origin persisted after flashover. Also, if the origin fire had a longer time to transfer heat to a wall prior to involving a large HRR fuel or prior to post-flashover, the origin pattern would be more distinct.

Another study was conducted by Claflin of ATF with the support of the Denver Fire Department [26]. Three fire experiments were conducted in instrumented, similarly furnished rooms with the same ignition scenario. Each room had a different ventilation configuration. One room had an open door at the time of ignition, a second room had an open door at ignition and a window that opened at flashover, and a third room had the door and window opened at the time of ignition. The fires were ignited and allowed to burn two minutes post-flashover before they were extinguished. These experiments also demonstrated that origin fire patterns generated pre-flashover can exist and be located after a post flashover exposure.

Because fire investigators typically investigate fires in structures consisting of more than one or two rooms, it is important to conduct research in structures that represent a range of residential structures that reflect real world conditions in terms of building volume, areas of origin, and different flow path arrangements. Extending the finding of the previous research to residential structure influenced the design of the current study.

2 Objectives

The goal of this study is to improve the capabilities of the fire investigation community by adding to the knowledge base and transferring the findings as widely as possible in order to get the science to the street.

The primary objectives of this series of experiments as presented in this report include:

1. To examine how differences in ventilation to full-scale structure fires result in changes to the fire damage and fire patterns within the structure.
2. To measure the fire environment within the structures and compare the data with the fire damage in the structures.
3. To document the repeatability or lack thereof of the fire conditions and fire patterns within a structure based on the available ventilation.
4. To provide a discussion of basic fire dynamics in structures, specifically with regard to the impact of ventilation on the resulting fire patterns.

3 Experimental Configuration

All experiments described in this report were conducted at full scale in purpose-built residential style structures with variable ventilation configurations. The design of the structures, fuel loads, and types of experiments were planned during a workshop with the technical panel assembled for this study. The test structures included an approximate 111 m^2 (1200 ft^2) single-story ranch structure and a 297 m^2 (3200 ft^2) two-story colonial. The colonial had a two-story family room and open foyer.

The structures were designed by a residential architectural company to represent a popular legacy and a popular modern design. These designs have been used in several previous UL FSRI firefighting ventilation research studies [22, 23].

The single story, traditional ranch style structure was designed to represent a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.44 m (8 ft) ceilings. By the 1950s, ranch style homes comprised nine out of ten houses built in America. Ranch homes are still the most popular style of home in 34 states across the United States. [27].

The two story, contemporary colonial style structure was designed to represent a more current design that incorporated an open plan arrangement, a two story foyer and a two story family room. According to the U.S. Census Bureau, 50% of the single family houses built in 2017 were two story houses, 45% had four bedrooms, and 37% of the two story houses had an open two story foyer [28].

The test scenarios ranged from fires in the structures with no exterior ventilation to room fires with flow paths that connected the fires with remote intake and exhaust vents. Elevated fires originating in the kitchens were also examined. In total, 13 experiments were conducted in the single-story structure and eight experiments were conducted in the two-story structure. All experiments were conducted at UL's Large Fire Laboratory in Northbrook, IL. Tables 3.1 and 3.2 show the 13 experiments conducted in the single story structure and the eight experiments conducted in the two story structure including the fire location and ventilation, respectively.

Table 3.1: Experiments in Single Story Structure

Exp #	Fire Location	Ventilation
1	Living Room	All Vents Closed
2	Living Room	All Vents Closed
3	Living Room	Front Door Open
4	Living Room	Front Door Open
5	Living Room	Front Door and Bedroom 3 Window Open
6	Kitchen	All Vents Closed
8	Kitchen	All Vents Closed
10	Kitchen	Front Door Open
11	Kitchen	Front Door Open
7	Bedroom 1	All Vents Closed
9	Bedroom 1	All Vents Closed
12	Bedroom 1	Front Door and Bedroom 1 Windows Open
13	Bedroom 1	Front Door and Bedroom 1 Windows Open

Table 3.2: Experiments in Two Story Structure

Exp #	Fire Location	Ventilation
1	Family Room	All Vents Closed
2	Family Room	Front Door Open
3	Family Room	Front Door and Bedroom 3 Window Open
4	Family Room	Front Door and Bedroom 2 Window and Bedroom 4 Window Open
8	Family Room	Front Door and Family Room Window Open
5	Kitchen	Front Door Open
6	Laundry Room	Front Door Open
7	Den	Front Door Open

3.1 Single Story Structure

The single story, ranch-style structure had overall interior dimensions of 13.92 m (46 ft) by 7.7 m (25 ft). The layout of the structure included three bedrooms, a living room, a dining room, and a kitchen. There were also areas, normally designed as a bathroom and closets, that were walled-off from the structure that provided protection to the installed instrumentation. Figure 3.1 shows a dimensioned plan view drawing of the ranch structure indicating major interior dimensions.

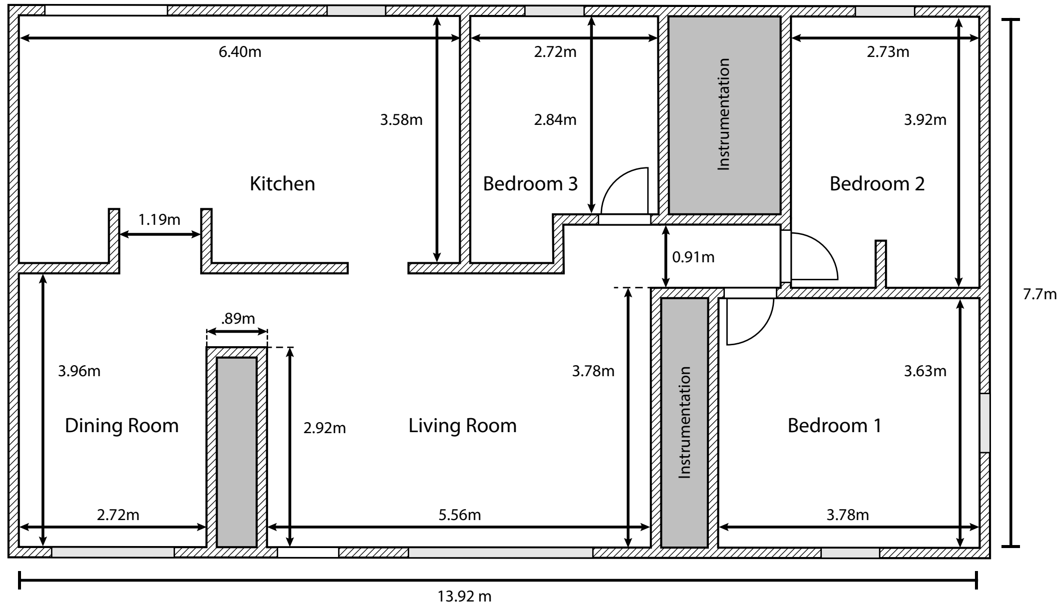


Figure 3.1: Plan view dimensioned drawing of the single story structure.

The walls were constructed from nominal dimensional lumber, 38.1 mm by 88.9 mm (nominally 2 in. x 4 in. studs). The studs were lined with two layers of gypsum board. The base layer was 15.9 mm (0.625 in) thick regular gypsum wallboard. The top or finish layer was 12.7 mm (0.5 in.) thick light gypsum wallboard. The ceiling supports were constructed from engineered lumber I-joists and were covered with gypsum wallboard in the same manner as the walls. The floor was constructed from nominal dimensional lumber, 38.1 mm by 88.9 mm (nominally 2 in. x 4 in. studs) and covered with a 18.3 mm (0.72 in.) thick plywood sub floor. On top of the plywood was either 12.7 mm (0.5 in) cement board, or when applicable, 0.609 cm (0.25 in.) plywood, padding, carpet, or vinyl flooring were installed. The exposed wood, vinyl, or carpeted floor areas were dictated by the location of the burn rooms and the flow paths.

The single story structure had two exterior doors (front and back), three bedroom doors, and a doorway that led to the kitchen. All doors/doorways had a height of 2.05 m (6 ft, 8 in.). The interior doors, were purchased hollow-core wood frame doors. To repeatably control ventilation (i.e., size and timing of opening), the exterior vent enclosures (windows) were purpose-built as side-hinged shutters. Each shutter was wood-framed and finished with a layer of insulation on the inside with a layer of 12.7 mm (0.5 in) plywood on the outside. The shutters were affixed to the exterior of the framed window openings. For windows greater than 1.0 m in width, shutters were installed on each side of the opening and met in the middle when closed. Note that one of the two shutters had a lip installed to overlap the gap where two shutters would meet. These shutters allowed for the windows to be manipulated open and closed as many times as needed during the experimental series. The ability of the shutter to open fully at a designated time was a particular benefit to this design. This functionality is not possible with a standard glass window insert. Window shutters like this are common in fire service training props. Figure 3.2 shows the location of the interior and exterior vents in the single story structure, with Table 3.3 showing the size of the windows.

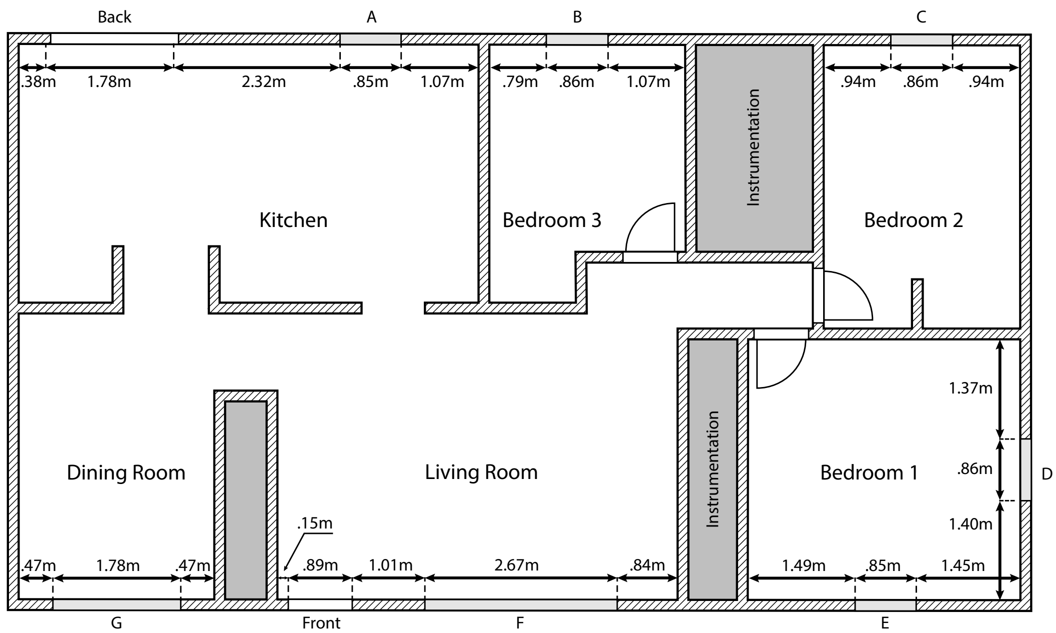


Figure 3.2: Plan view dimensioned drawing of the vents in the single story structure.

Table 3.3: Single Story Structure Window Sizes and Sill Heights

Window	Size	Sill Height
A	0.85 m x 1.02 m	1.07 m
B	0.86 m x 1.46 m	0.61 m
C	0.86 m x 1.46 m	0.61 m
D	0.86 m x 1.46 m	0.61 m
E	0.85 m x 1.46 m	0.61 m
F	2.67 m x 1.46 m	0.61 m
G	1.78 m x 1.46 m	0.61 m

To characterize ventilation within the single story structure, a leakage test was conducted with all exterior vents closed. ASTM E 779, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization," was followed to determine the air changes per area and the equivalent leakage area [29]. The leakage in the test structure was 4 air changes per hour (ACPH) at 50 Pa (0.007 psi) with an equivalent leakage area of 0.08 m^2 (0.9 ft^2) at 10 Pa (0.0014 psi). Equivalent leakage area is defined as the area of a sharp-edged hole that would have the same leakage flow rate as the building if both were subjected to a 10 Pa pressure difference. For a single story residential structure, a tight house would have 3.5 ACPH50, a moderately tight house would have 8.8 ACPH50, a typical house would have 17.5 ACPH50, and a leaky house would have 35 ACPH50 [30]. Considering the uncertainty in typical pressure measurements, the test structure fell between a tight and moderately tight structure.

3.2 Two Story Structure

The two story, or colonial-style, structure had overall interior dimensions of 15.05 m (49 ft) by 10.13 m (33 ft). The layout of the first floor included a living room, den, family room, kitchen, laundry room, dining room, and entrance foyer on the first floor. The first floor included two areas that were 'walled-off' from the structure that provided protection to the installed instrumentation. Figure 3.3 shows a dimensioned plan view drawing of the first floor of the two story structure indicating major interior dimensions.

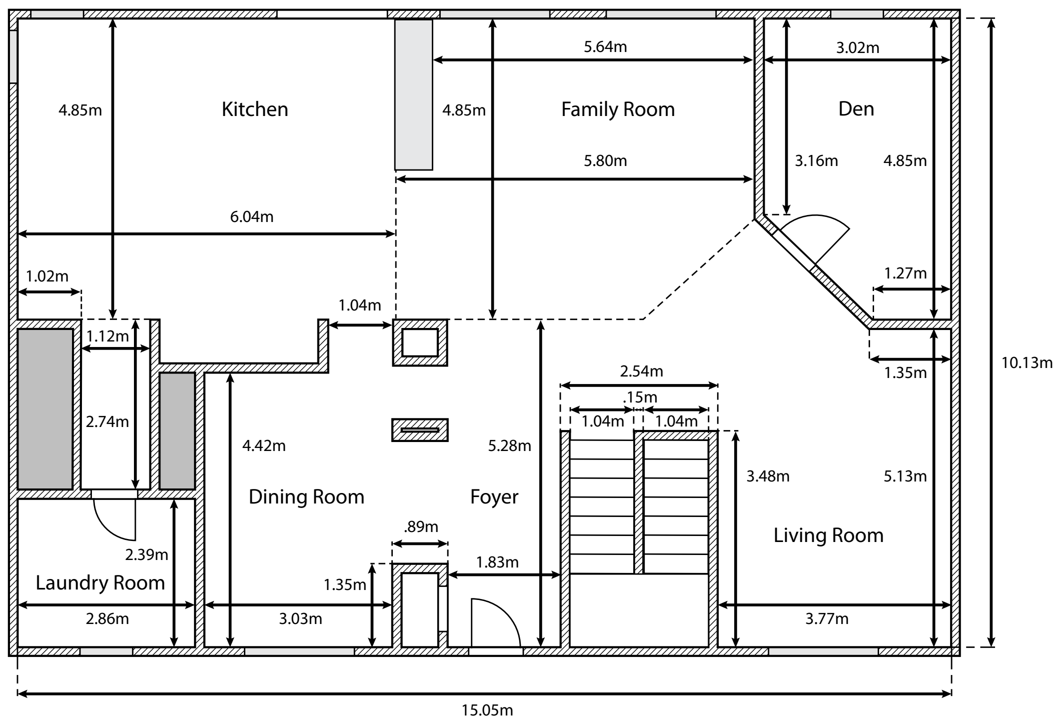


Figure 3.3: Plan view dimensioned drawing of the first floor of the two story structure.

The second floor had the same interior dimensions as the first floor, with four bedrooms and two rooms that were walled-off from the structure that provided protection to the installed instrumentation. Note, the areas above the first floor family room and above the foyer were open to the first floor. Figure 3.4 shows a dimensioned plan view drawing of the second floor of the two story structure indicating major interior dimensions and the areas open to the floor below.

Similar to the single story, the walls were constructed from nominal dimensional lumber, 38 mm by 89 mm (nominally 2 in. by 4 in. studs). The studs were lined with two layers of gypsum board. The base layer was 15.9 mm (0.625 in.) thick regular gypsum wallboard. The top or finish layer was 12.7 mm (0.5 in.) thick light gypsum wallboard. The ceiling supports for the upper level were constructed from engineered lumber I-joists and were covered with gypsum wallboard in the same manner as the walls. The floor for the upper level was supported by nominal dimension joists, 38 mm by 286 mm (nominally 2 in. by 12 in.) and covered with 18.3 mm (0.72 in.) thick plywood sub floor. The floor of the lower level was constructed from nominal dimension lumber, 38 mm

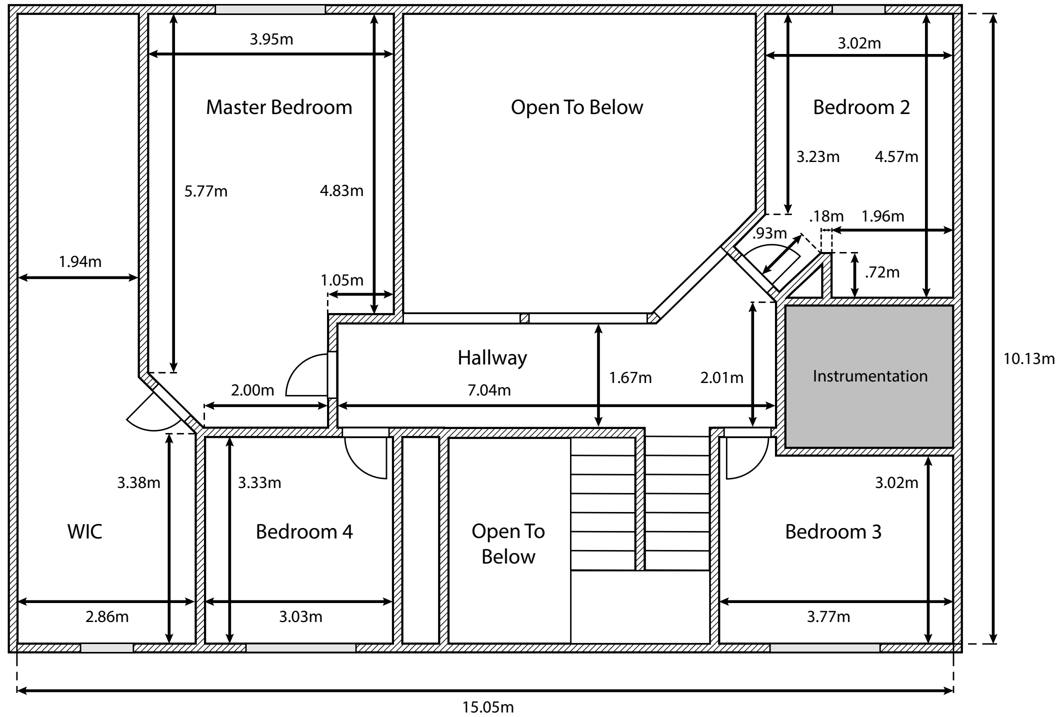


Figure 3.4: Plan view dimensioned drawing of the second floor of the two story structure.

by 89 mm (nominally 2 in. by 4 in. studs) and covered with 18.3 mm (0.72 in.) thick plywood sub floor. On top of the plywood was either 1.27 cm (0.5 in.) cement board or when applicable, 0.609 cm (0.25 in.) plywood, padding, carpet, or vinyl flooring were installed. The exposed wood, vinyl, or carpeted floor areas were dictated by the location of the burn rooms and the flow paths.

The two story structure had two exterior doors (front and back) and six interior doors (four bedrooms, laundry room, and den). All doors had a height of 2.05 m (6 ft, 8 in). The interior doors, were purchased, interior, hollow core, wood frame doors. To repeatably control ventilation size and timing of opening, the exterior vents (doors and windows) were purpose built in the same fashion as the single story structure. Figure 3.5 shows the location of the interior and exterior vents in the first floor of story structure, with Table 3.4 showing the size of the windows.

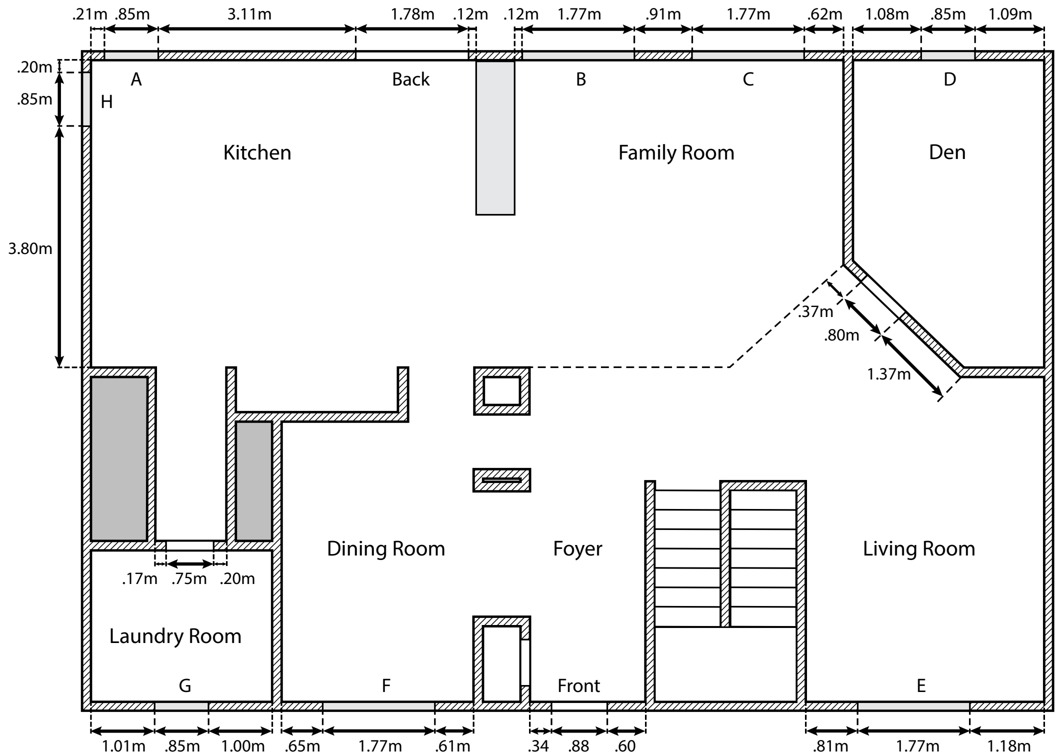


Figure 3.5: Plan view dimensioned drawing of the vents in the first floor of the two story structure.

Table 3.4: Two Story Structure, First Floor Widow Sizes and Sill Heights

Window	Size	Sill Height
A	0.85 m x 0.85 m	1.22 m
B	1.77 m x 1.45 m	0.61 m
C	1.77 m x 1.45 m	0.61 m
D	0.85 m x 1.46 m	0.61 m
E	1.77 m x 1.46 m	0.61 m
F	1.77 m x 1.46 m	0.61 m
G	0.85 m x 1.46 m	0.61 m
H	0.85 m x 0.85 m	1.22 m

Figure 3.6 shows the location of the interior and exterior vents in the second floor of the two story structure with Table 3.5 showing the size of the windows. For the second story hallway, the height of the interior wall that opens to the first floor was 0.95 m (37 in.) as shown in rows N, O, and P in Table 3.5.

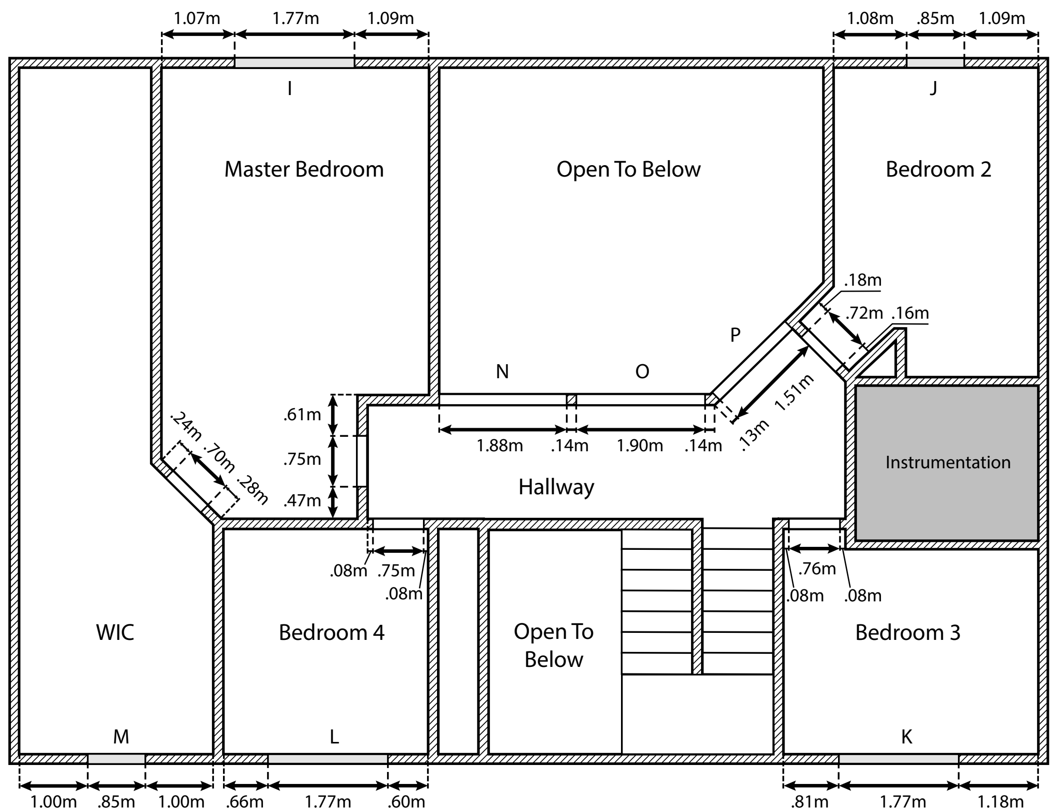


Figure 3.6: Plan view dimensioned drawing of the vents in the second floor of the two story structure.

Table 3.5: Two Story Structure, Second Floor Window Sizes and Sill Heights

Window	Size	Sill Height
I	1.77 m x 1.46 m	1.22 m
J	0.85 m x 1.46 m	0.61 m
K	1.77 m x 1.46 m	0.61 m
L	1.77 m x 1.46 m	0.61 m
M	0.85 m x 1.46 m	0.61 m
N	1.88 m x 1.26 m	0.95 m
O	1.90 m x 1.26 m	0.95 m
P	1.51 m x 1.26 m	0.95 m

ASTM E 779 tests were also conducted with the two story structure to estimate the air leakage in terms of air changes per hour and the equivalent leakage area [29]. The leakage in the two story structure was 4 ACPH50 with an equivalent leakage area of 0.18 m^2 (2.0 ft^2) at 10 Pa (0.0014 psi). As with the single story structure, the two story leakage values were between a tight house and a moderately tight house.

3.3 Instrumentation

Instrumentation was installed to measure gas temperature, gas pressure, and gas movement within the structures. In addition, oxygen sensors were installed to determine when a sufficient level of oxygen was available for flaming combustion.

Gas temperatures were measured with both 1.3 mm (0.05 in) bare-bead, Chromel-Alumel (type K) thermocouples and 1.6 mm (0.0625 in) inconel sheathed thermocouples. Expanded uncertainties as high as 20% for upper layer temperatures measured by a 1 mm bare-bead type K thermocouple have been reported by researchers at NIST [31, 32]. Small diameter (approximately 0.25 mm) thermocouples were used during these experiments to limit the impact of radiative heating and cooling. The total expanded uncertainty associated with the temperature measurements from these experiments is estimated to be ± 15%. Sheathed thermocouples were used in conjunction with the bi-directional probes for gas velocity measurements. Pressure measurements were made using differential pressure sensors to determine pressure changes relative to ambient pressure (outside of the structure) conditions. The differential pressure sensor was a Setra Model 264 with a range of ± 125 Pa. The total expanded uncertainty associated with pressure measurements obtained from the transducers is estimated as ± 10%. A gas velocity measurement study examining flow through doorways in pre-flashover compartment fires yielded expanded uncertainties ranging from ± 14% to ± 22% for measurements from bi-directional probes similar to those used during this series of tests [33].

Oxygen sampling ports were installed in the structures. The sampling ports consisted of 9.5 mm (3/8 in.) stainless steel tubing within the structure. Once outside the structure, the sample was filtered through a coarse, Solberg Model 842, 2 micron paper filter before being drawn through a condensing trap to remove moisture. At the condensate trap exit, the sample line transitioned from stainless steel to polyethylene tubing for flexibility. Upstream of the analyzer the sample passed through a drying tube dry fine, Perma Pure Model, 1 micron FF-250-E-2.5G filter. To minimize transport time through the system, samples were pulled from the structure through the use of Cole Palmer Model L-79200-30 vacuum/pressure diaphragm pump rated at 0.75 CFM. Gas samples were analyzed through the use of eight OxyMat6 Siemens oxygen analyzers, which used the paramagnetic alternating pressure method. The gas sampling instruments used throughout the series of tests discussed in this report have demonstrated a relative expanded uncertainty of ±1% when compared to span gas volume fractions [34].

All numerical data was recorded with a National Instruments data acquisition system specifically programmed software that incorporated a SCXI-1001 chassis with eight SCXI-1102C 32-Channel modules each connected to a TC-2095 end terminal with built-in cold junction compensation for thermocouple measurements. The TC-2095 could also accept 0-10 V DC for non-thermocouple measurements. The system was configured for a total of 256 channels with a 1 Hz sample rate. A separate system was used for each structure.

Standard video and firefighting IR cameras were also installed inside of the structures to capture information about the fire dynamics of the experiments. Video cameras were also positioned outside of the structures to monitor the flow of smoke, flames, and air at the exterior vents. To ensure video capture even if the cameras experienced thermal failure, the cameras are hardwired to a digital video recorder outside the structure.

The next two sections will present the layout of the instrumentation for the experiments carried out in the single story and two story structure. Table 3.6 shows the icons used in the instrumentation floor plans in Sections 3.3.1 and 3.3.2.

Table 3.6: Instrumentation Legend

Icon	Instrumentation
	Thermocouple Array
	Gas Velocity
	Pressure Tap
	Oxygen Concentration Tap (O_2)
	Video Camera

3.3.1 Single Story Structure

Instrumentation locations remained relatively static for the single story experiments except for the location of the oxygen measurements and the IR cameras. Due to the change in the primary location of fuels in the subsets of the experimental series (living room, kitchen, bedroom 1) combined with the finite number of oxygen measurements (maximum of eight per experiment) and finite number of IR cameras available during the experiments (maximum of two per experiment), those sensors needed to be moved. The oxygen measurement locations were chosen to capture oxygen levels near the area of origin and in the path of where combustion would flow. The IR cameras were moved to best capture the fire dynamics around the area of origin. Standard cameras were installed in the same locations across experiments, but those not used do not appear on the specific instrument plans. As a result, specific instrumentation plans exist for the three fire locations: Figure 3.7 is the living room, Figure 3.10 is bedroom 1, and Figure 3.9 is the kitchen.

For the instrumentation installed in fixed locations such as thermocouple arrays, pressure taps, and gas velocity probes, their respective spatial locations within the structure can be found on any of the three instrument plans. Each thermocouple array consisted of eight type-K thermocouples. The top thermocouple in each array was located 2.54 cm (1 in) below the ceiling with the remaining seven spaced at 30.5 cm (1 ft) intervals (30.5 cm below ceiling, 61 cm below ceiling ... 213 cm below ceiling). Three pressure taps were installed at each spatial location at elevations of 30.5 cm (1 ft), 122 cm (4 ft) and 213 cm (7 ft) below ceiling. Velocity probes were installed in relevant doorways, windows, and the interior hallway based on the location of fire. In each case, the five probes in the array were evenly spaced within the respective location. The probe in the windows were spaced 0.24 m (0.79 ft) apart. Therefore the top probe in the windows was 0.61 m (2.0 ft) below the ceiling and the bottom probe in the windows was approximately 1.6 m (5.2 ft) below the ceiling. See Table 3.3 for the heights of the vents.

Figure 3.7 shows the dimensioned instrumentation locations for the experiments with a living room ignition with all vents closed or with the front door open. The temperature and gas velocity measurements at the front door and bedroom 3 window were only utilized for experiments where either the front door or bedroom window were opened. This was true for measurements at the front door for the other two fire locations. Oxygen measurements were made at four spatial locations: the front door, the kitchen doorway, the hallway, and along the front wall. At each location, measurements were made at 2 elevations, at 10 cm (4 in) above the floor and 121 cm (4 ft) above the floor. These locations were designed to best quantify the fire dynamics within the living room.

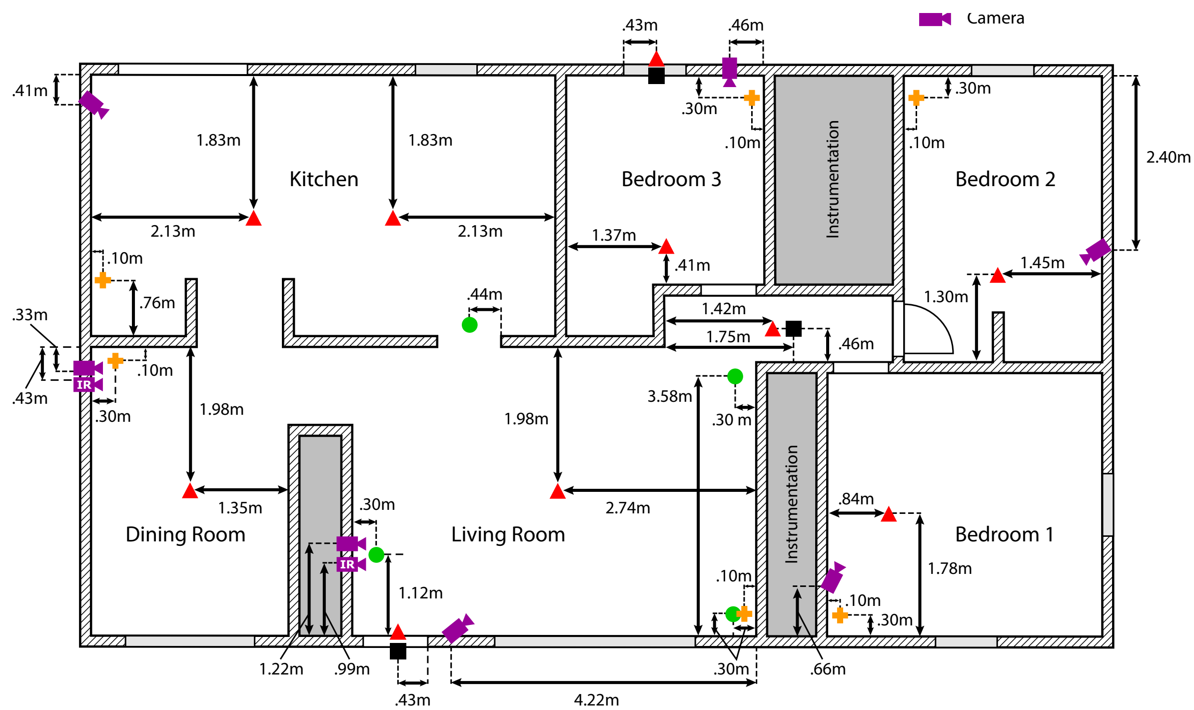


Figure 3.7: Plan view dimensioned drawing of instrumentation in the single story structure for living room fires.

For the experiments where the front door and bedroom 3 window were open, the oxygen probes at the 10 cm (4 in.) above the floor and 121 cm (4 ft) elevations that were located at the kitchen doorway were moved to be centered at the open window. Figure 3.8 shows the dimensioned locations of the instrumentation in the single story for oxygen sensors moved from the kitchen to the bedroom.

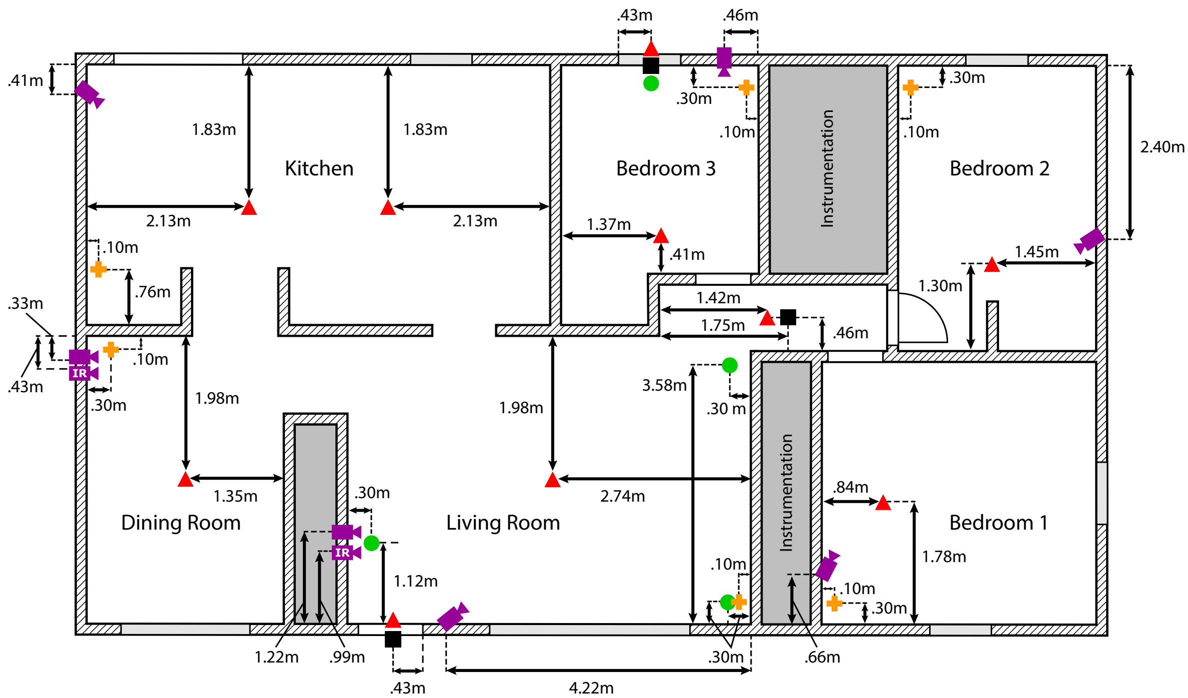


Figure 3.8: Plan view dimensioned drawing of instrumentation in the single story structure for living room fire with open front door and open bedroom 3 window.

Figure 3.9 shows the dimensioned instrumentation locations for the experiments with a kitchen ignition. Similar to the living room and bedroom 1 fires, oxygen sensors were installed at the front door and kitchen doorway at 10 cm (4 in) above the floor and 121 cm (4 ft) above the floor. To capture oxygen depletion toward the bedrooms, the 10 cm (4 in.) above the floor probe was installed in the hallway. The remaining three oxygen measurements locations were in the kitchen, at 10 cm (4 in) above the floor and at 121 cm (4 ft) above the floor probe in the far corner of the kitchen, as well as at 10 cm (4 in) above the floor probe installed through the lower kitchen cabinets.

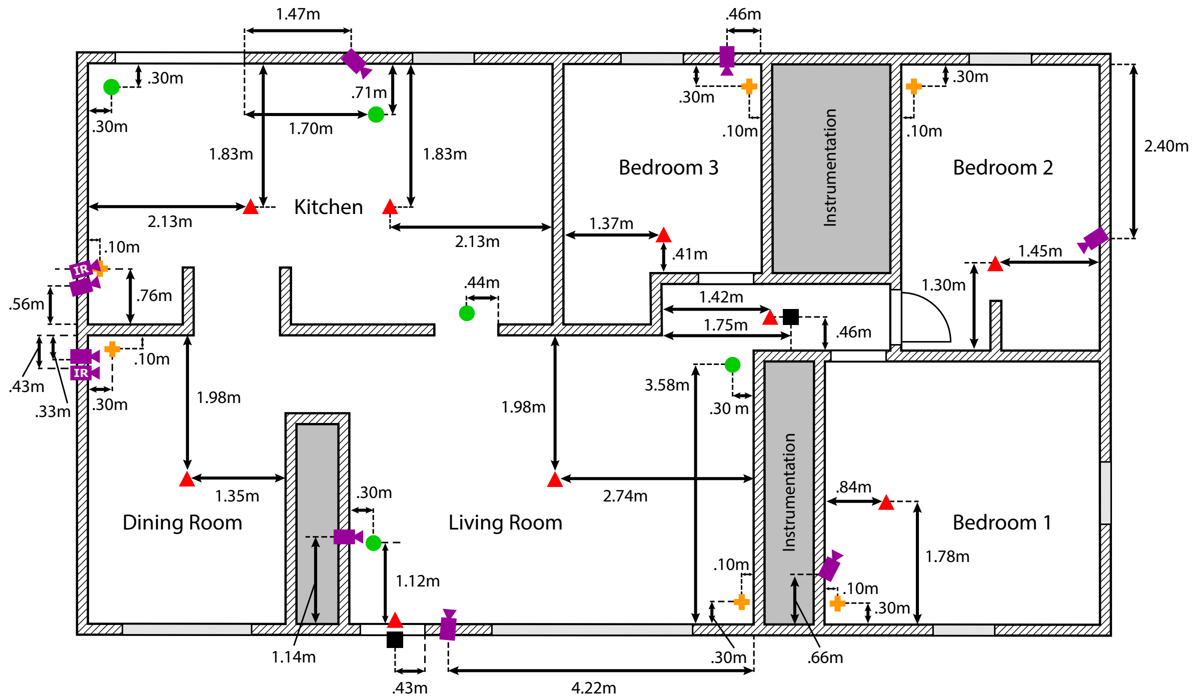


Figure 3.9: Plan view dimensioned drawing of instrumentation in the single story structure for kitchen fires.

For the bedroom 1 fires, a dimensioned instrument plan appears in Figure 3.10. For the bedroom tests, there were five spatial locations for the eight available oxygen measurement points. The front door and kitchen doorway each had the same sampling points at the two elevations used in the living room fires: 10 cm (4 in) above the floor and 121 cm (4 ft) above the floor. The remaining four sampling points were installed at three locations within bedroom 1. At the bedroom doorway, there was a sampling point at 10 cm (4 in) above the floor. The final two measurement points were installed 10 cm (4 in) above the floor, one below the front window and one below the side window.

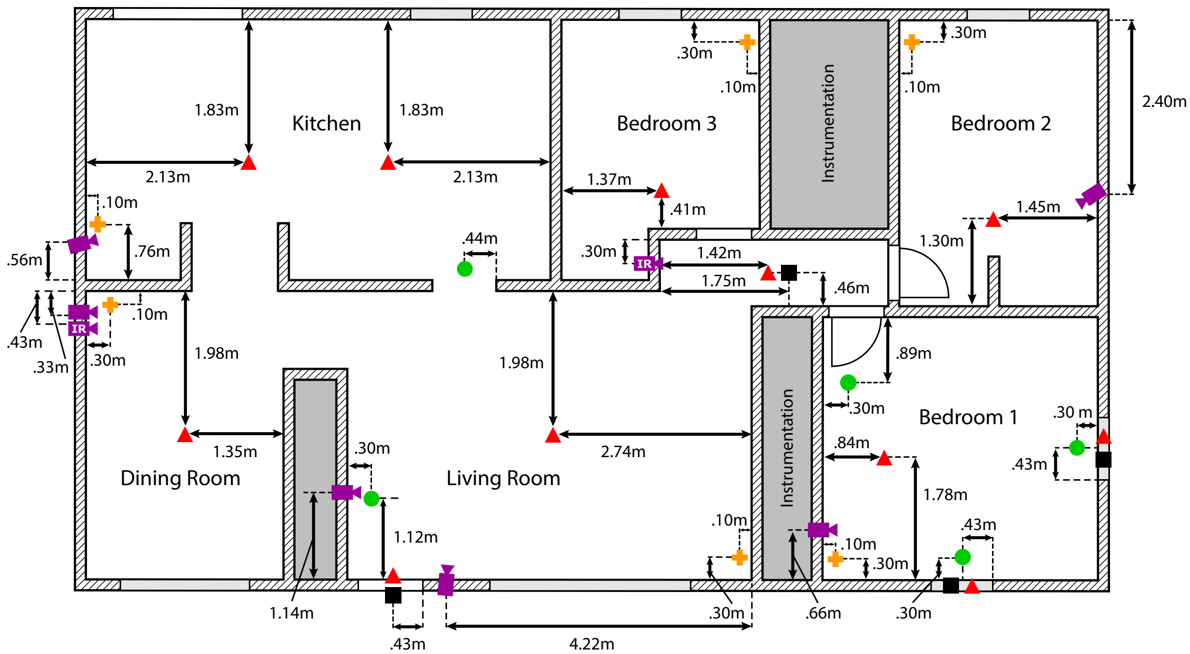


Figure 3.10: Plan view dimensioned drawing of instrumentation in the single story structure for bedroom 1 fires.

In all three instrument plans, one of the IR cameras was installed at the dining room wall to capture fire dynamics and gas flows of the living room, hallway, and kitchen doorway. The second IR camera was moved to specifically capture images more direct to the respective fire location.

3.3.2 Two Story Structure

In similar fashion to the single story structure, instrumentation in the two story remained fairly constant throughout the eight experiments. For the instrumentation installed in fixed locations such as thermocouple arrays, pressure taps, and gas velocity probes, their respective spatial locations within the structure can be found on any of the three instrument plans. Thermocouple arrays consisted of either eight or 16 type-K thermocouples. There were three 16-thermocouple arrays installed in the two story structure: two in the family room and one in the foyer. The remainder of the thermocouple arrays had eight probes. In all cases, the top thermocouple in each array was located 2.54 cm (1 in.) below the ceiling with the remaining thermocouples spaced at 30.5 cm (1 ft) intervals (30.5 cm below ceiling, 61 cm below ceiling ... 213 cm below ceiling). Three pressure taps were installed at each spatial location at elevations of 30.5 cm (1 ft), 122 cm (4 ft) and 213 cm (7 ft) below ceiling in all locations except the family room. Because the family room was open to the second floor, the three pressure elevations were 30.5 cm (1 ft), 244 cm (8 ft) and 460 cm (15 ft) below ceiling. Velocity probes were installed in relevant doorways, windows, and the interior hallway based on the location of fire. In each case, the five probes in the array were evenly spaced within the respective location.

Due to the limited number of oxygen sensors and IR cameras, those sensors were relocated based on the location of the ignition. Recall from Table 3.2 that five experiments were conducted in the two story structure with an ignition in the family room. For four of the five experiments, the oxygen sensors and IR cameras were in the same locations and only seven oxygen sensors were used. These experiments included: all vents closed, only the front door open, the front door and bedroom 3 window open, and the front door and family room window open. Figures 3.11 and 3.12 show the dimensioned instrumentation for the first and second floor of the structure, respectively. In these experiments, there were seven oxygen sensors on the first floor (Figure 3.11); four oxygen sensors at the left side of the family room as it transitioned into the kitchen at 10 cm (4 in.) and 1.22 m (4 ft) above the floor and at 10 cm (4 in.) and 1.22 m (4 ft) below the ceiling, one sensor on the right side of the family room at 10 cm (4 in.) above the floor and two sensors at the front door at 10 cm (4 in.) and 1.22 m (4 ft) above the floor.

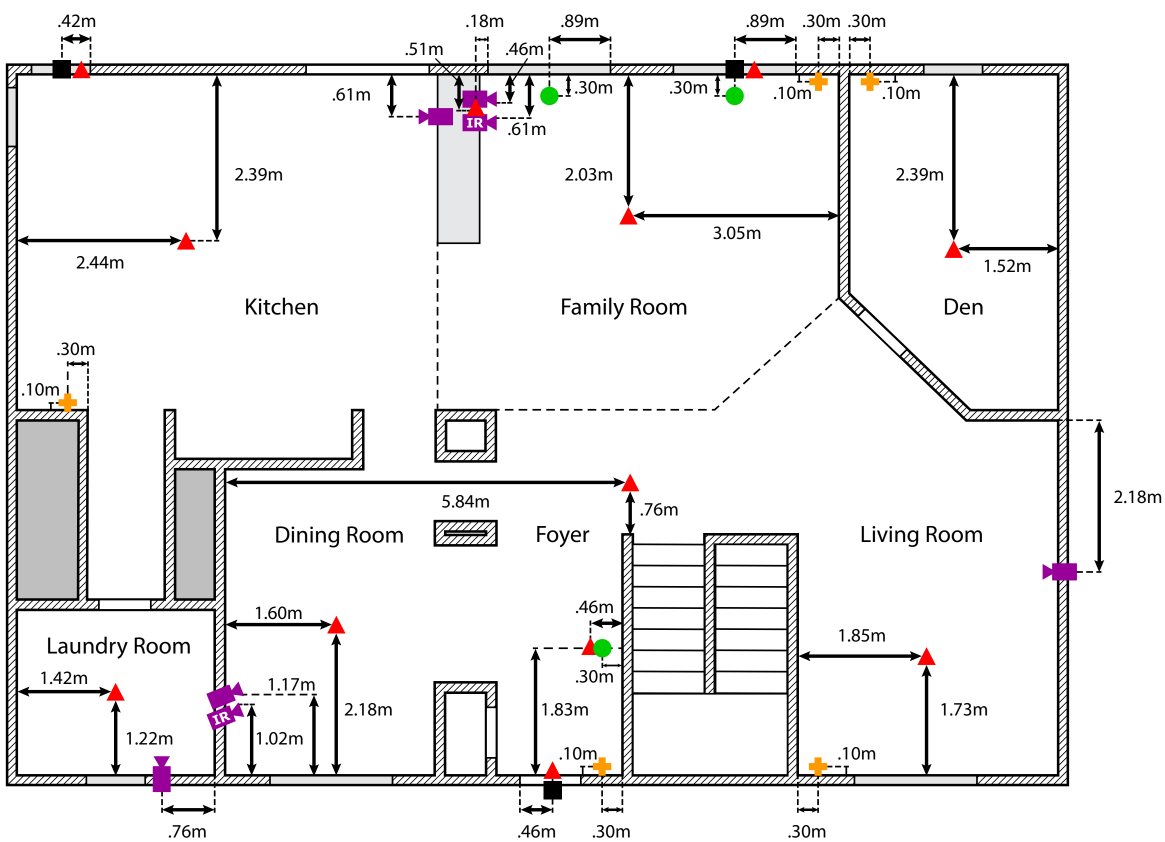


Figure 3.11: Plan view dimensioned drawing of instrumentation of the first floor of the two story structure for family room fires.

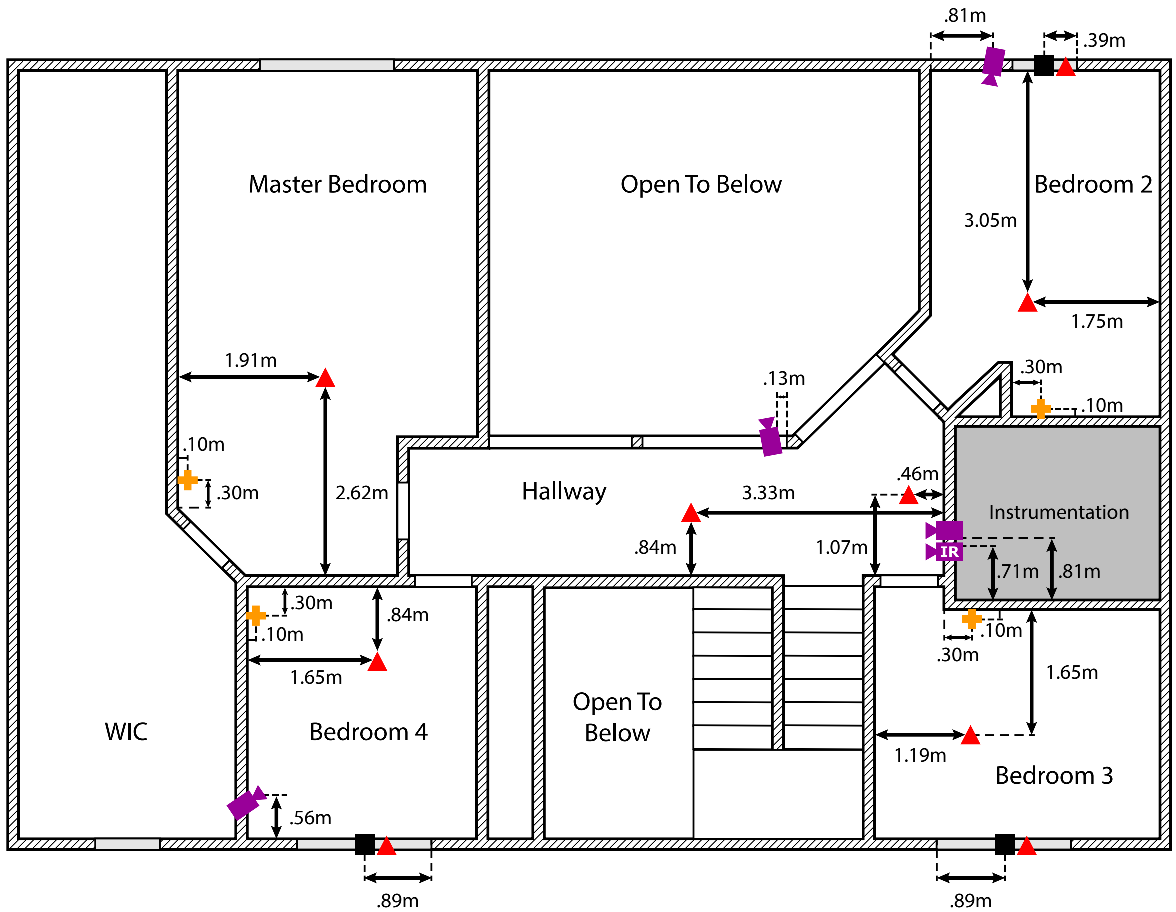


Figure 3.12: Plan view dimensioned drawing of instrumentation of the second floor of the two story structure for four family room fires: all vents closed, front door open, front door and bedroom 3 window open, and front door and family room window open.

For the fifth family room experiment, five oxygen sensors were located on the first floor and three were located on the second floor. The first floor oxygen sensor locations were in the same spatial locations compared to the other family room experiments, but the vertical locations changed. Two first floor sensors were located at the front door at 10 cm (4 in) and 1.22 m (4 ft) above the floor while the other three were located in the family room. One was on the right side of the family room at 10 cm (4 in) above the floor. The remaining other two were located on the left side of the family as it transitioned into the kitchen at 10 cm (4 in) and 1.22 m (4 ft) above the floor. The three sensors on the second floor were in bedrooms 1, 2, and 3 at 10 cm (4 in) above the floor. Refer to Figure 3.11 for the spatial locations of the sensors on the first floor and Figure 3.13 for the dimensioned instrumentation of the second floor of the structure.

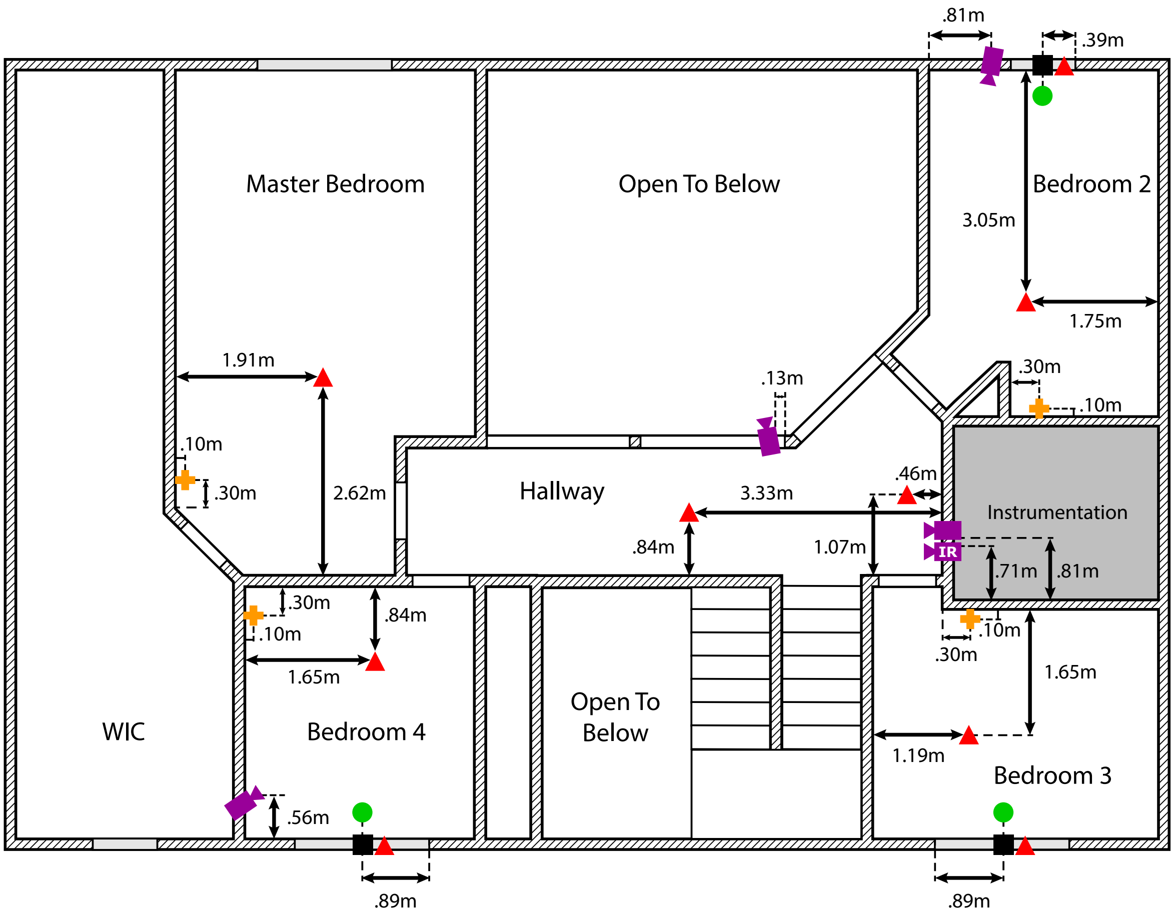


Figure 3.13: Plan view dimensioned drawing of instrumentation of the second floor of the two story structure for family room fire with front door and bedroom 2 and bedroom 4 windows open.

All of the oxygen sensors for the kitchen, laundry room, and den experiments were installed on the first floor of the structure. In the kitchen experiment, the sensors were paired for 10 cm (4 in) and 1.22 m (4 ft) above the floor elevations at four locations within the structure: at the front door, the left side of the family room as it transitioned into the kitchen, at the kitchen cabinets along the back wall of the kitchen, and at the start of the hallway from the kitchen to the laundry room. Figure 3.14 shows the dimensioned instrumentation layout of the first floor for the kitchen fire experiment.

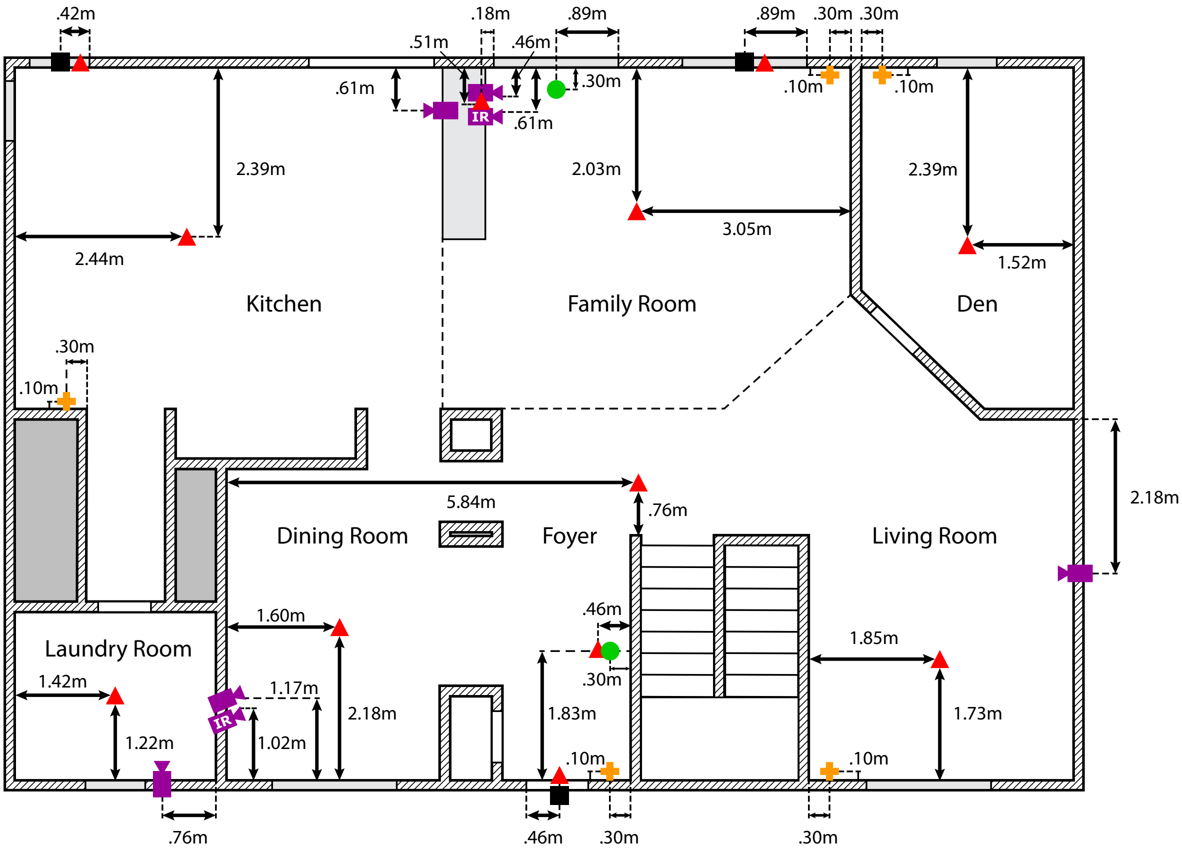


Figure 3.14: Plan view dimensioned drawing of instrumentation of the first floor of the two story structure for kitchen fire.

For the laundry room fire, the oxygen sensors were all paired at two elevations: 10 cm (4 in) and 1.22 m (4 ft) above the floor. The four locations were the front door, in the kitchen where cabinets along the back wall were installed for the kitchen fire experiments, the laundry room doorway, and in the corner opposite the door to the laundry room. A dimensioned layout of the first floor instrumentation used in the experiment with a laundry room ignition is included in Figure 3.15.

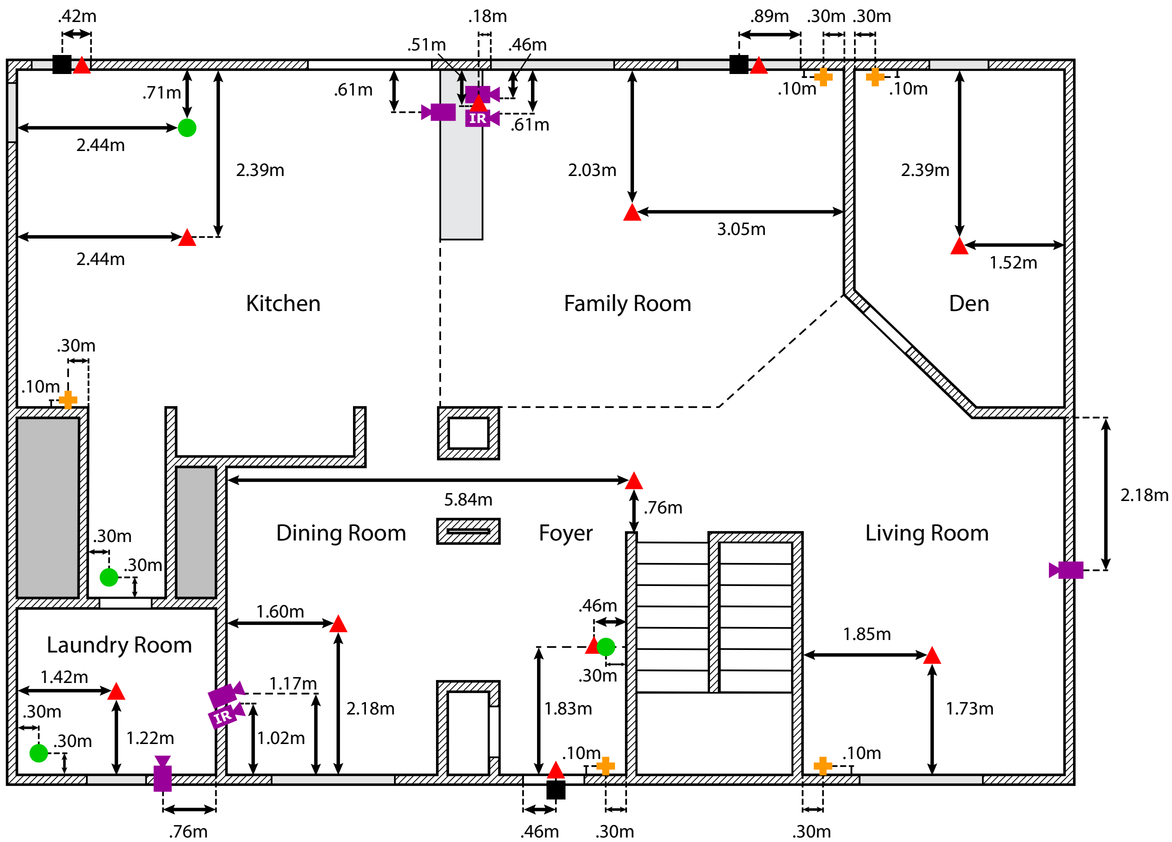


Figure 3.15: Plan view dimensioned drawing of instrumentation of the first floor of the two story structure for laundry room fire.

In the case of the fire started in the den, six of the eight oxygen sensors were located in the den. The two sensors remote from the den were installed at the front door at 10 cm (4 in) and 1.22 m (4 ft) above the floor. In the den, there were three locations, each with two elevations of 10 cm (4 in) and 1.22 m (4 ft) above the floor. Two of the locations were along the window side wall in the left and right corners of the room. The third location was in the corner of the room opposite the wall with the window. Figure 3.16 shows the dimensioned instrumentation layout of the first floor for the den fire experiment.

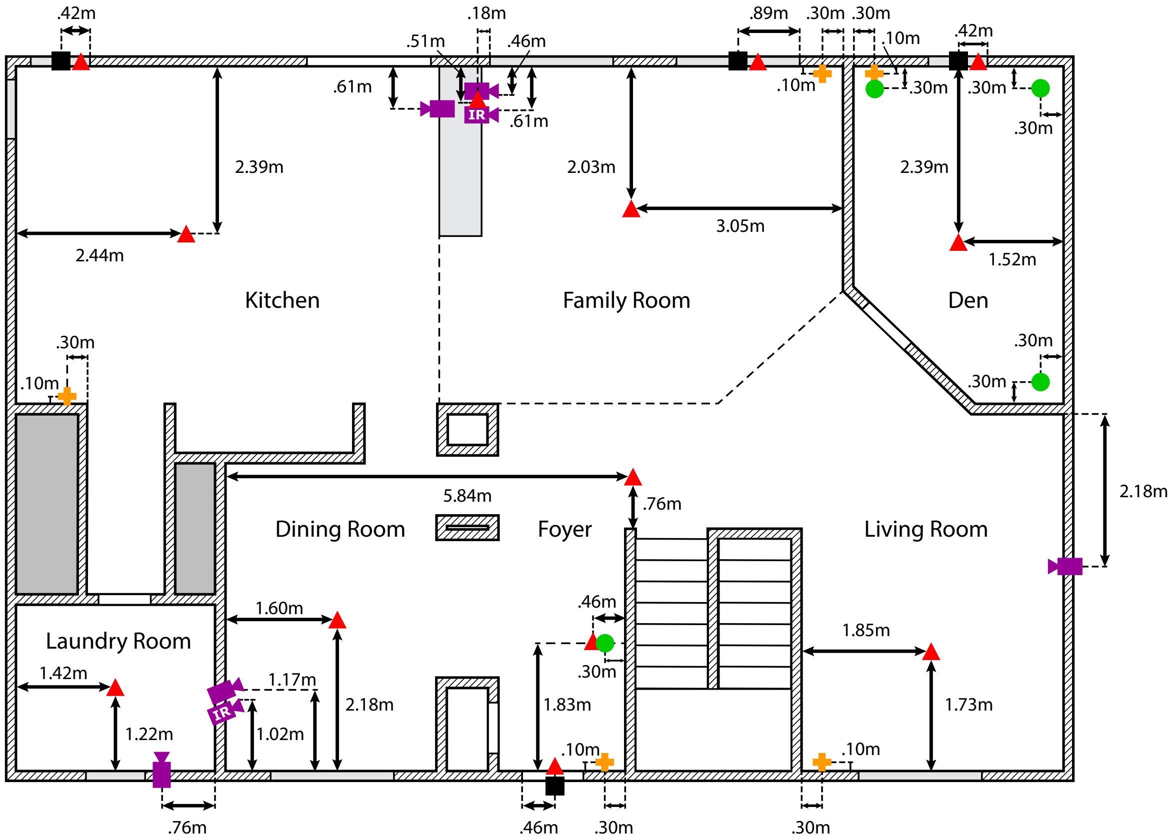


Figure 3.16: Plan view dimensioned drawing of instrumentation of the first floor of the two story structure for den fire.

The second story instrumentation was the same for the kitchen, laundry room, and den experiments. A plan view of the second floor instrumentation is included in Figure 3.17.

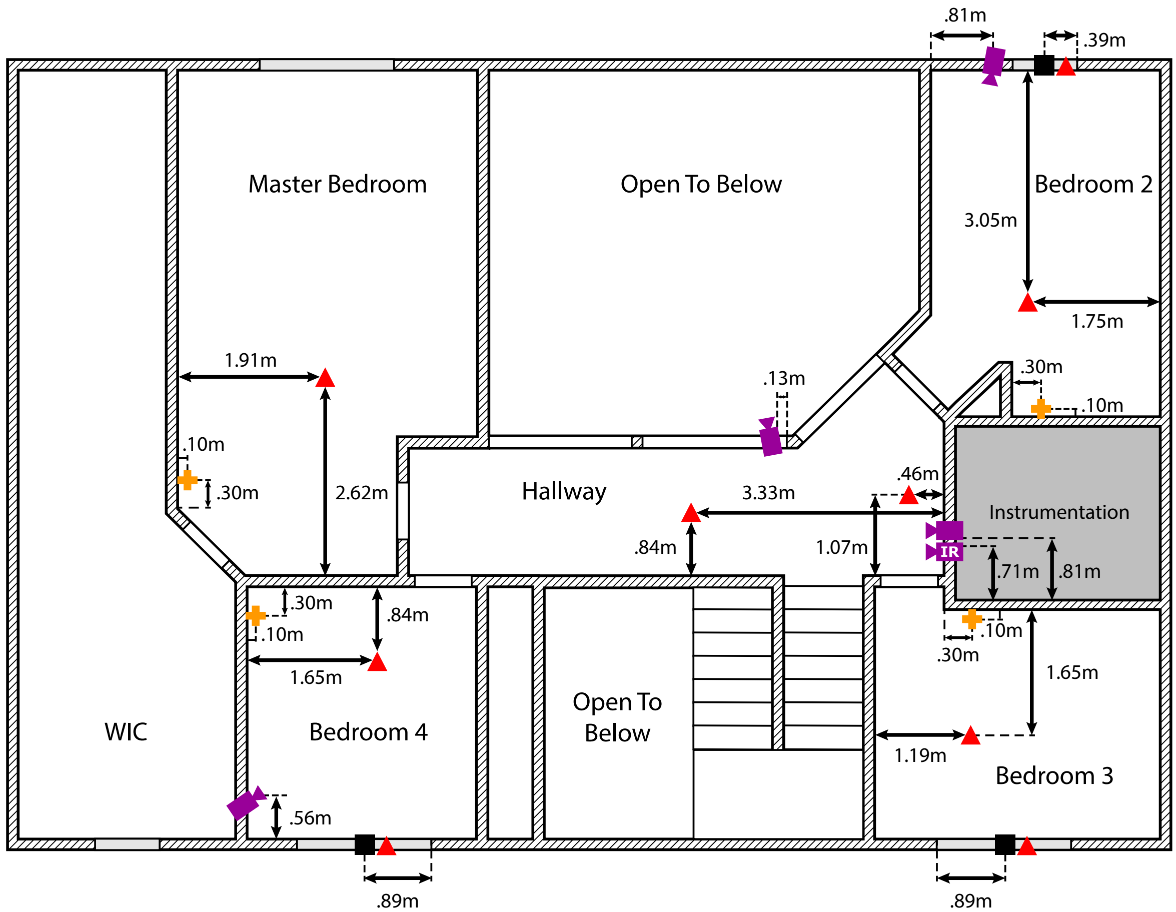


Figure 3.17: Plan view dimensioned drawing of instrumentation of the second floor of the two story structure for kitchen, laundry, and den fires.

3.4 Fuel Load

For both the single story and two story structure, the fuel load was composed of similar components based on room type. Tables 3.7, 3.8, and 3.9, show the size, weight, and major material composition for the fuel items in the living room, kitchen, or bedroom, respectively. The key fuels are listed in the tables. The values given in the table for carpet, padding, vinyl floor, and plywood sub-floor are for the single story. The flooring materials were larger for the two story. The gypsum wallboard, painted with latex paint, also had potential to contribute to the total fuel load in each room.

The living rooms had a number of small items, such as a floor lamp, two table lamps, an electric clock, a telephone, and a remote control for the TV, which were located around the room. These items were composed of metal, plastics, and some fabric. All totaled, the small items added up to 15 kg (33 lbs). The total fuel package mass in the living room was 418 kg (919 lbs) as shown in Table 3.7.

Table 3.7: Living Room Fuel Load

Item	Length [cm]	Width [cm]	Height [cm]	Weight [kg]	Material
Sofas Multi-fabric	193.0	81.3	89	39.5	Seat cushion: 82% puf, 18% polyester batting, body:69% polyester fiber, 31% cotton, 23% puf, wood frame
Cushioned Chair	81.3	73.7	94	17.5	wood frame, polyurethane cushions
Circular End Table	61.6	61.6	56	14.6	wood
Coffee Table	76.8	46.4	41	11.6	solid wood frame, particle board top and sides
TV Stand (Dresser)	56.2	91.4	87	54.4	wood and plywood
TV	89.5	55.9	23	5.9	plastic and glass
Plywood Sub-floor	556	396	1.2	153	plywood
Carpet Padding	556	396	1.0	10.2	polyurethane
Carpeting	556	396	1.2	24.9	polyester pile, polypropylene backing

The kitchen fire experiments added a number of fuel elements to the test series that were different from the living room and bedroom fire experiments. The ignition was located approximately 0.9 m (3 ft) above the floor, the fuel package consisted of many solid fuels, including particle board cabinets, plastics and plastic laminates, and vinyl floor covering. The ignition package included an electrically modified coffee maker (all thermal fuse protection was removed). The 12-cup, plastic shrouded coffee maker had 50 0.23 L (8 fl. oz) capacity expanded polystyrene hot serve cups weighing 0.1 kg (0.2 lbs) arranged in three stacks on the right of the coffee maker and a 0.45 kg (16 oz) bag of potato chips on the left side.

The fuel with the most mass in the kitchens were the wall and base cabinets. The kitchen table and chairs were located at the wall most remote from the range. These were installed as target fuels to see if the main body of fire would ignite damage or ignite them. Target fuels were also installed in the living room. Those fuels included carpet, padding, sub-floor, a bookcase, and a sofa. There was a similar arrangement in the two story kitchen, although it included an additional base cabinet and additional 3.3 m^2 of vinyl floor. In the two story, the floor area of the family room was similar to the floor area of the living room in the single story. The total mass of the fuel package installed in the kitchen was 470.5 kg (1035 lbs).

In addition, the cabinet above the ignition package included: 1 kg (2.2 lb) of 0.53 L (18 oz) capacity polyethylene terephthalate (PET) drinking cups, 4.5 kg (9.9 lb) of 0.47 L (16 fl. oz.) capacity unexpanded polystyrene cups, and a 0.45 kg (16 oz) bag of potato chips. The kitchen fuel load appears in Table 3.8.

Table 3.8: Kitchen Fuel Load

Item	Length [cm]	Width [cm]	Height [cm]	Weight [kg]	Material
Kitchen Table (Square)	66.0	66.0	62	13.2	particleboard and wood
Dining Chair	55.9	48.3	95	7.2	wood frame, batting, metal spring
Toaster	28.6	16.5	19	0.9	plastic and metal
Coffee Maker	29.21	17.1	30	1.2	plastic
Waste Container	43.5	34.0	69	1.8	polypropylene
Sub-floor	646.4	373.4	1.2	167.6	plywood
Sheet Flooring	366.8	366.8	0.2	13.2	vinyl
Wall Cabinets	500	30.5	76.2	148.6	oak doors and veneer, particle board boxes
Base Cabinets	457	61.0	87.6	206.4	oak doors and veneer, particle board boxes
Counter Tops	518	64.8	1.9	69.6	plastic laminate over particle board
Bookcase (LR)	29.2	62.5	181	20.9	particleboard
Sofa (LR)	195.6	88.9	77	115.7	polyurethane foam 50%, polyester fiber 50%, wood frame
Sub-floor (LR)	556	396	1.2	153	plywood
Carpet Padding (LR)	556	396	1.0	10.2	polyurethane
Carpeting (LR)	556	396	1.2	24.9	polyester pile, polypropylene backing

The total mass of the fuel package items installed in a bedroom was 221.5 kg, (487.3 lbs). The hallway and living room were carpeted as part of the fuel package outside of the room of origin for the single story. A bookcase and a sofa were also positioned in the living room as target fuels. Table 3.9 shows the fuel components of a bedroom.

Table 3.9: Bedroom Fuel Load

Item	Length [cm]	Width [cm]	Height [cm]	Weight [kg]	Material
King Mattress	200.7	180.3	25	34.5	52% polyurethane foam, 30% blended cotton batting 18% polyester fiber batting
King Box Spring	198.1	88.9	18	20.9	59% fiber pad, 41% cotton batting, wood frame
Pillow	59.7	43.2	10	0.7	100%polyester fill, cover - 100% cotton
Mattress Topper	196.9	193.7	12	9.1	polyurethane foam
Pillow Cases	101.6	60.3		0.1	60% cotton, 40% polyester
Comforter	254.0	228.6	4	2.7	60% cotton, 40% polyester fabric 100% polyester filling
Sheets	274.3	259.1		0.9	60% cotton, 40% polyester
Upholstered Chair	79.4	78.7	99	24.5	75% polyester fiber body with 25% puf; 90% puf cushion with 10% polyester batting
Dresser	91.4	56.2	87	54.4	wood and plywood
Night Stands	49.5	48.3	62	20.9	particle board and plywood
Wood Table Lamp	18.4	13.0	62	3.5	particle board and metal
Square Lamp Shade	43.8 (bottom) 26.1 (top)	36.2 18.4	23	0.5	cloth and plastic
Bed Frame					metal
Waste Container	17.8	28.4	27	0.3	polypropylene
Sub Floor	378	363	1.2	95.4	plywood
Carpet Padding	378	363	1.2	6.3	polyurethane
Carpeting	378	363	0.9	15.5	polyester pile, polypropylene backing
Bookcase (LR)	29.2	62.5	181	20.9	particleboard
Sofa (LR)	195.6	88.9	77	115.7	50% polyurethane foam , polyester fiber 50%, wood frame
Plywood Sub-floor (LR)	556	396	1.2	153	plywood
Carpet Padding (LR)	556	396	1.0	10.2	polyurethane
Carpeting (LR)	556	396	1.2	24.9	polyester pile, polypropylene backing

The laundry room fire was ignited in a laundry basket, with two pillows and a comforter, on top of the washing machine. In addition to the fuel load listed in Table 3.10, the cabinet above the dryer included 4.5 kg (9.9 lb) of 0.47 L (16 fl. oz) capacity unexpanded polystyrene cups. A metal lamp with a fabric shade weighing 0.3 kg was located on the console table. Carpet, padding, and sub-floor were installed in the foyer near the open front door to serve as a target fuel. The washer and dryer in the laundry room were composed mainly of steel, so they were not considered part of the fuel load. The total mass of the fuel load in the laundry room was 133.8 kg (294.4 lbs). This mass does not include the fuels on the floor of the hallway or the foyer.

Table 3.10: Laundry Room Fuel Load

Item	Length [cm]	Width [cm]	Height [cm]	Weight [kg]	Material
Laundry Basket	70.5	46.0	28.0	1.0	polypropylene
Pillow	59.7	43.2	10	0.7	100% polyester fill, 100% cotton cover
Comforter	264.2	233.7	3	2.1	100% polyester fill, 100% cotton cover
Pillow Cases	101.6	60.3		0.1	60% cotton, 40% polyester
Group A Plastic Commodity	53	53	52	7	4.5 kg unexpanded polystyrene cups, 2.5 kg cardboard
Wood Floor	286	239	1.2	47.6	plywood
Wall Cabinet	122.0	30.5	76.2	40	oak doors with particle board box
Console Table	121.9	40.6	74.9	15.6	particleboard
Wood Floor (hallway)	274	112	1.2	21.4	plywood
Plywood Sub-floor (Foyer)	528	183	1.2	67.3	plywood
Carpet Padding (Foyer)	528	183	1.0	4.4	polyurethane foam
Carpeting (Foyer)	528	183	1.2	10.9	polyester pile, polypropylene backing

The fuel package in the den was composed of furnishings as well as carpet, padding, and sub-floor (see Table 3.11). The total mass of the fuel package in the den was 297 kg (312 lbs). In addition, the flow path between the den and the front door was carpeted, and two target sofas were located in the living room.

Table 3.11: Den Fuel Load

Item	Length [cm]	Width [cm]	Height [cm]	Weight [kg]	Material
Sofa	195.6	88.9	77	115.7	polyurethane foam 50%, polyester fiber 50%, wood frame
Upholstered Chair	83.8	88.9	85.0	29.5	75% puf, 25% polyester batting
Ottoman	50	65	40	9.7	polyurethane foam 50%, polyester fiber 50%, wood frame
Console Table	121.9	40.6	74.9	15.6	particleboard
Coffee Table	96.5	51.0	55.2	11.5	particleboard
Metal Lamp with Shade	35.6	35.6	70.7	2.6	shade made of fabric with wire frame 0.3 kg
Wood Floor	365	303	1.2	76.6	plywood
Carpet padding	365	302	1.0	5.1	polyurethane foam padding in den, family room, and foyer
Carpeting	365	302	1.2	12.5	polyester pile, polypropylene backing
Plywood Sub-floor (FR)	564	485	1.2	190.4	plywood
Carpet Padding (FR)	564	485	1.0	12.5	polyurethane
Carpeting (FR)	564	485	1.2	30.9	polyester pile, polypropylene backing
Plywood Sub-floor (Foyer)	528	183	1.2	67.3	plywood
Carpet padding (Foyer)	528	183	1.0	4.4	polyurethane foam
Carpeting (Foyer)	528	183	1.2	10.9	polyester pile, polypropylene backing
Sofa (LR)	195.6	88.9	77	115.7	polyurethane foam 50%, polyester fiber 50%, wood frame

3.4.1 Single Story Structure

The fuel loads used in the single story experiments were designed based on the ignition location. There were three distinct fuel load configurations used in the single story structure: living room, kitchen, and bedroom. While the fuel loads differed based on location, the same configuration was used for each replicate experiment.

For fires ignited in the living room, the fuel arrangement consisted of four rooms of fuel: living room, open bedroom (bedroom 2), and two closed bedrooms (bedrooms 1 and 3). The primary fuel load was in the living room and consisted of two sofas, two wood framed, upholstered chairs, two end tables with lamps, a floor lamp, a coffee table, and a TV stand with a TV (see Table 3.7). Figure 3.18 shows a dimensioned layout of the living room fuel package within the structure.

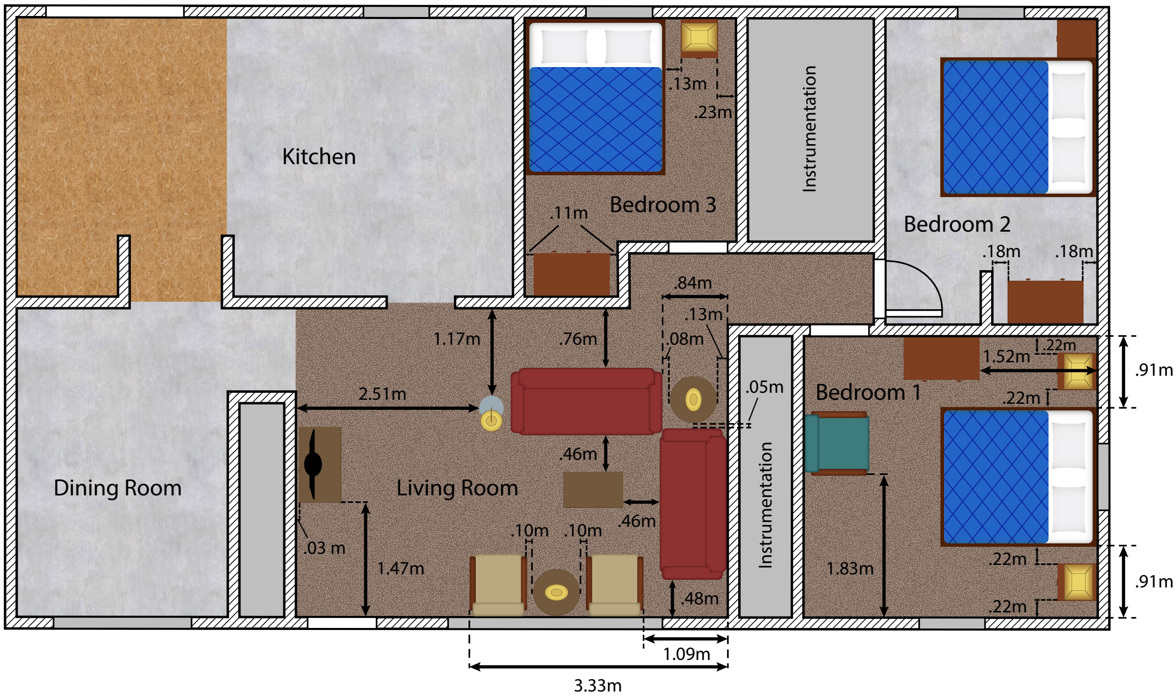


Figure 3.18: Plan view drawing of fuel configuration in the single story structure for living room fires.

The kitchen experiments fuel package included a full set of cabinets, a refrigerator, a stove, a coffee maker, a toaster, a kitchen table and chairs, and vinyl flooring. Two types of plastic cups and a bag of potato chips were positioned on the counter next to and in the cabinet above the coffee maker. In the living room, there was a bookcase, sofa, and carpeting, which acted as target fuels. Figure 3.19 provides a dimensioned plan view of the fuel configuration for experiments with a kitchen ignition, while Table 3.8 provides more detail on the fuel items.

Figure 3.19: Plan view drawing of fuel configuration in the single story structure for kitchen fires.

For the bedroom ignition experiments, the fire was always started in bedroom 1 even though each of the three bedrooms were furnished. Each bedroom had a unique fuel load based on the size of the bedroom. Bedroom 1 was furnished with a king-size bed with a puf pad and bedding, an upholstered chair, two night stands with lamps, a wood dresser, and carpeted floor. Figure 3.20 shows a dimensioned drawing of the fuel load for the bedroom ignition experiments, and more details about the fuel are included in Table 3.8. Similar to the kitchen experiments, there was a target sofa, bookcase, and carpeting in the living room.

Figure 3.20: Plan view drawing of fuel configuration in the single story structure for bedroom 1 fires.

3.4.2 Two Story Structure

In the two story structure, there were four different ignition locations: family room, kitchen, den, and laundry room. As a result, there were four different fuel configurations within the first floor of the structure. The family room configuration (see Figure 3.21) was setup similar to the living room on the single story: there were two sofas, two wood framed, upholstered chairs, two end tables with lamps, a free standing lamp, a coffee table, and a TV stand with a TV. Additionally, there were two target sofas in the living room.

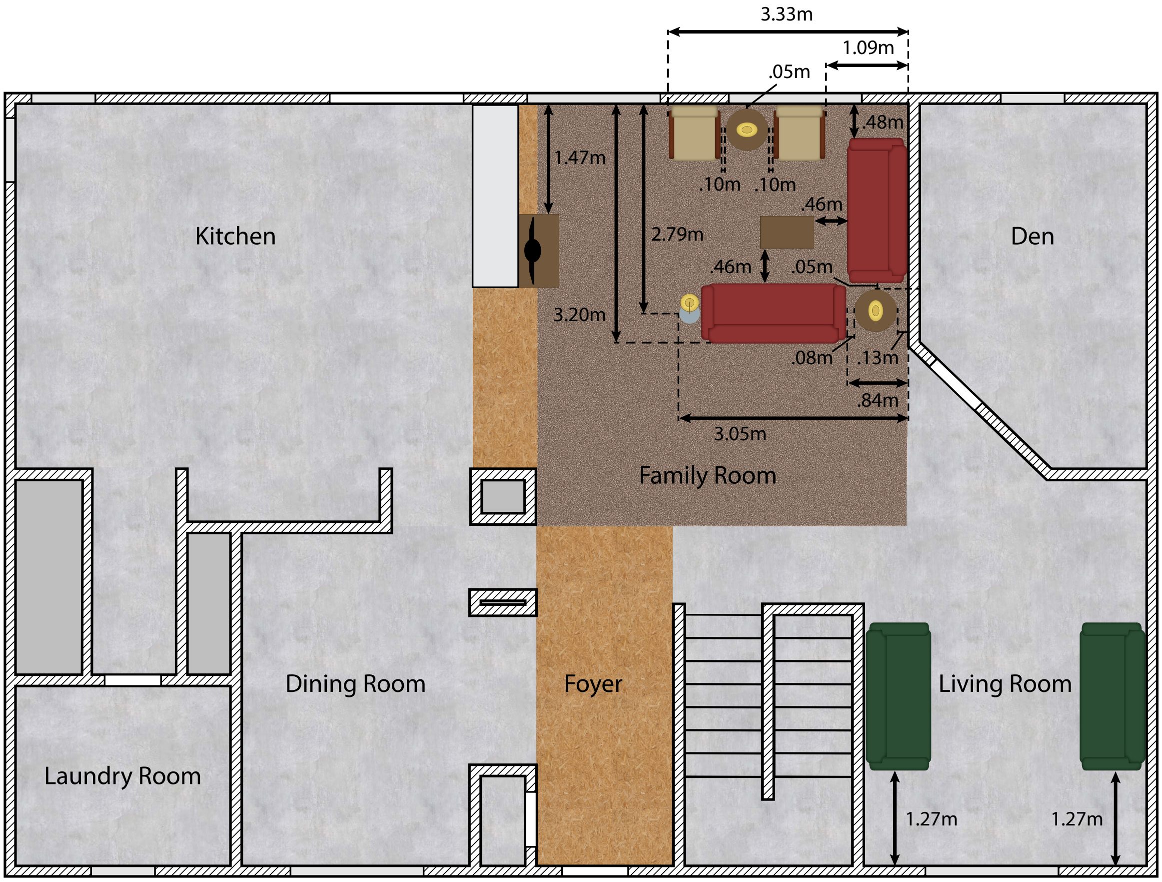


Figure 3.21: Plan view drawing of fuel configuration in the first floor of the two story structure for family room fires.

The kitchen fuel load included a full set of cabinets, a refrigerator, a stove, a coffee maker, a toaster, and a kitchen table and chairs. The cabinets above the coffee maker and toaster included consumable cups. In the living room, there were two sofas which acted as target fuels, one target sofa in the family room and a target bookcase in the foyer. Figure 3.22 shows the dimensioned layout of fuel on the first floor for a kitchen ignition.

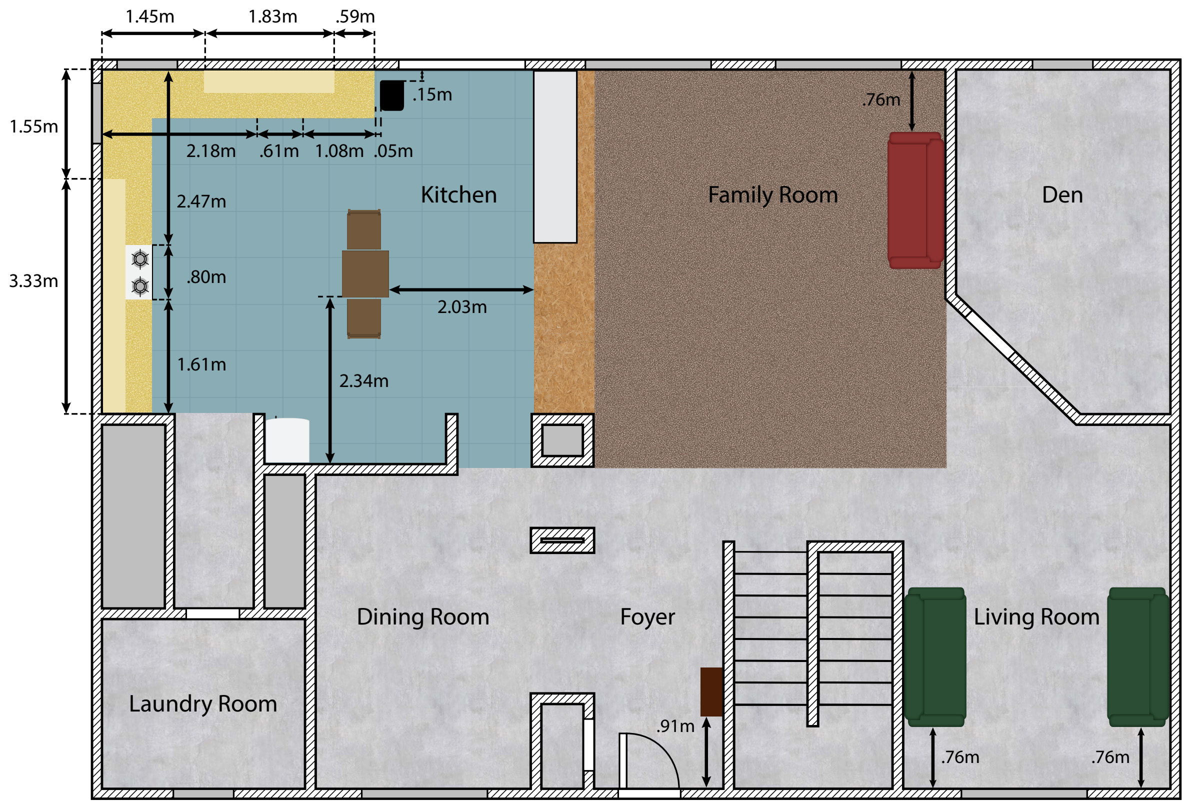


Figure 3.22: Plan view drawing of fuel configuration in the first floor of the two story structure for the kitchen fire.

The fuel load in the den consisted of a sofa, an upholstered chair with an ottoman, two console tables with lamps, and one small table. Figure 3.23 shows the dimensioned layout of fuel in the den as well as the two target sofas in the living room.

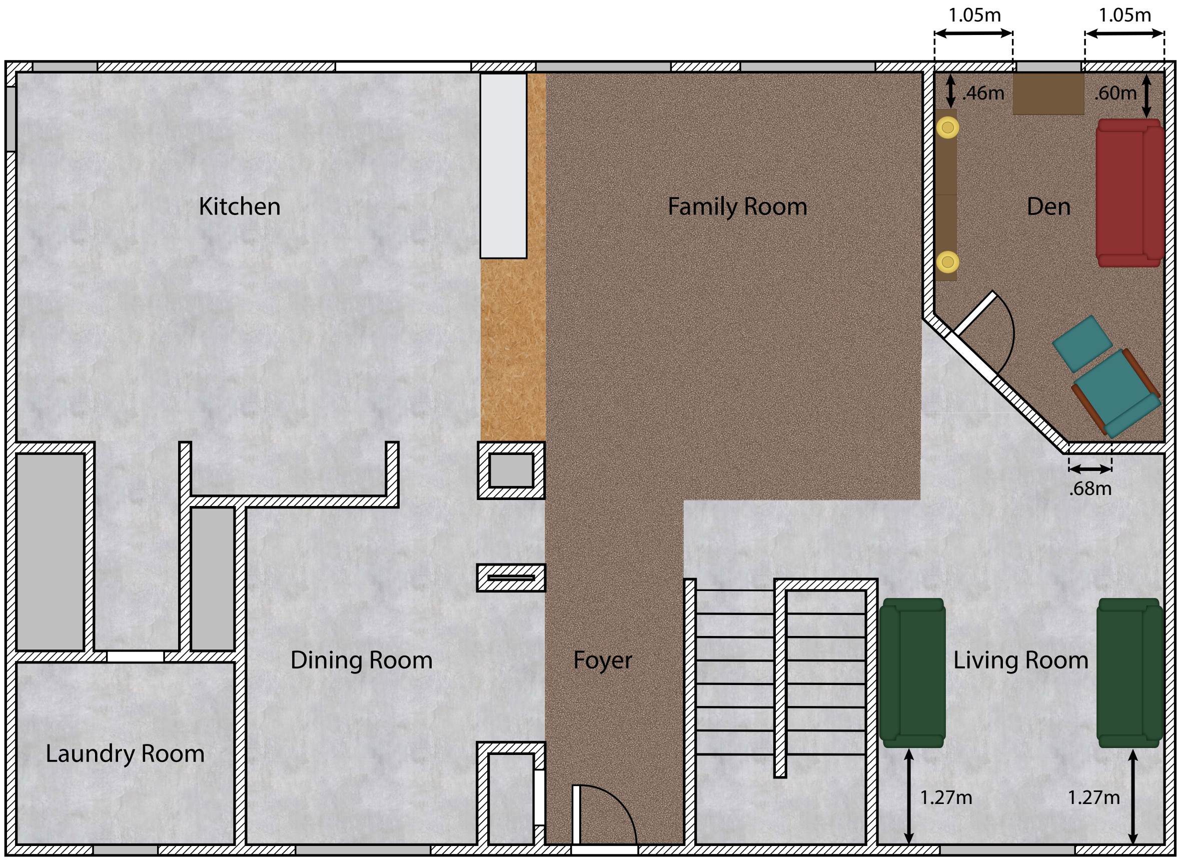


Figure 3.23: Plan view drawing of fuel configuration in the first floor of the two story structure for the den fire.

The fuel load for the laundry room included a washer, a dryer, a laundry basket with bed spread, and two pillows, two boxes of extruded polystyrene plastic cups, a small console table, and two wood cabinets. Additionally, there were two target sofas in the living room and one in the family room. A dimensioned drawing of the fuel load is included in Figure 3.24.

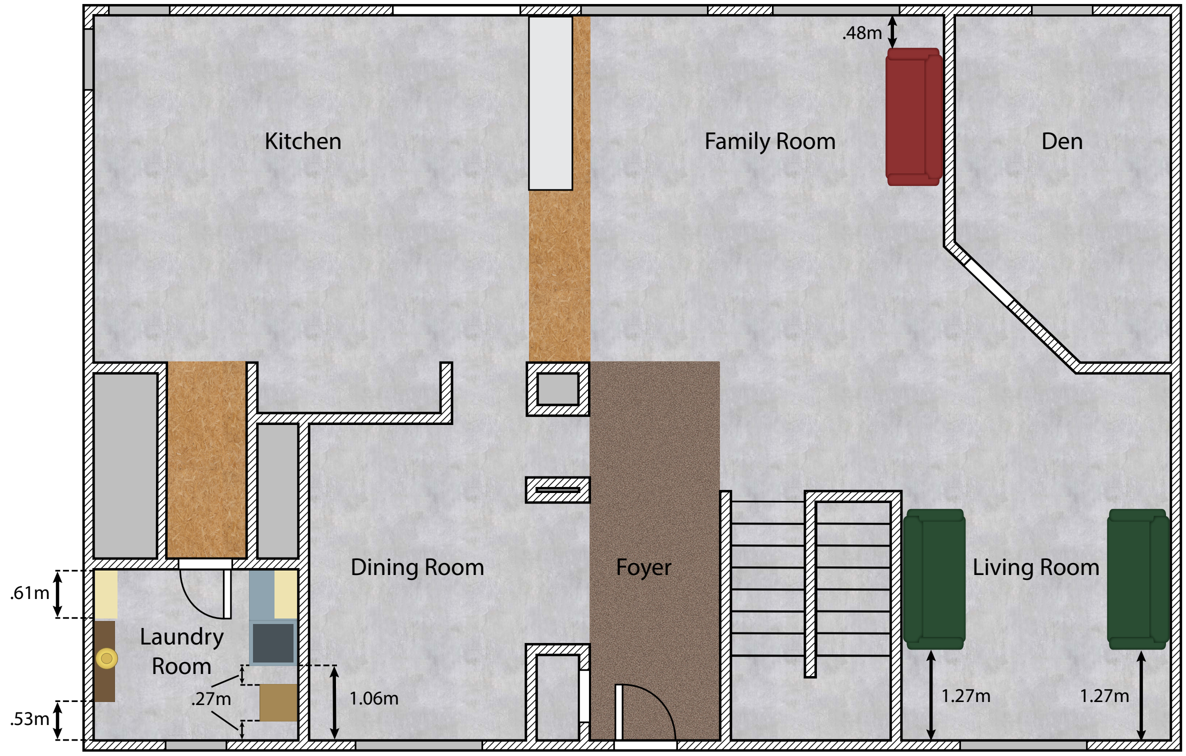


Figure 3.24: Plan view drawing of fuel configuration in the first floor of the two story structure for the laundry room fire.

For all experiments in the two story structure, the fuel load on the second floor remained the same. Each bedroom had a king-size bed, while three of four bedrooms (bedrooms 2, 3, and 4) also had a nightstand, lamp, and dresser. A dimensioned plan view of the second story fuel load is included in Figure 3.25.

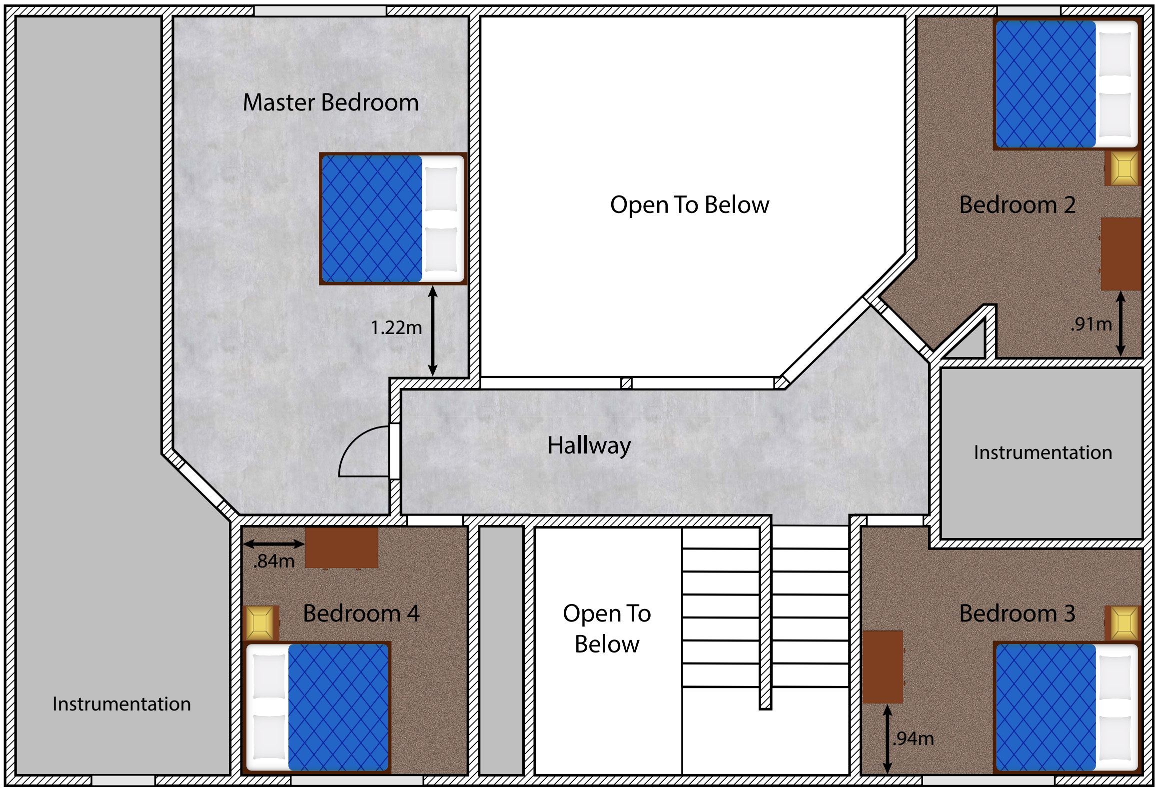


Figure 3.25: Plan view drawing of fuel configuration in the second floor of the two story structure.

3.5 Heat Release Rates of Key Furnishings

Upholstered furnishings located in the living rooms and bedrooms were burned under the UL oxygen consumption calorimeter to determine the heat release rate and the total heat released. The furnishings were purchased from a used furnishing dealer that bought sofas, chairs, and beds from hotels. These lots of furniture provided furnishings that were made by the same manufacturer, with similar build dates, and made of similar materials.

The oxygen consumption calorimeter used to quantify the fuels in these experiments is sized to handle up to a 10 MW fire with a 7.6 m diameter hood. Bryant and Mullholland [35] estimate the uncertainty of oxygen consumption calorimeters measuring high heat release rate fires at $\pm$ 11%. They identify several sources of error within the calorimeter, with one of the primary sources being the uncertainty in the gas concentration measurements. Note that for fires with sustained heat release rates above 10 MW, the uncertainty could be higher, with lower reported measurements as the volume of smoke produced could be greater than the volume of smoke that can be exhausted.

In both the single story and the two story structures, two sofas were positioned in the living room/-family room for the experiments where ignition occurred in those rooms, respectively. In each of those experiments, the sofa positioned against the wall was used as the point of ignition and the fire was started with an electric match. Wood framed, upholstered chairs were also positioned in each of the living room/family room experiments. These chairs served as target fuels. An electric match was also used to ignite the sofa and upholstered chair for the heat release rate experiment.

Three sofas were ignited and burned in the absence of a compartment and quantified using oxygen consumption calorimetry to understand the magnitude and repeatability energy release of one of the primary fuel packages used in these experiments. The heat release rate (HRR) as a function of time for the three sofas is included in Figure 3.26.

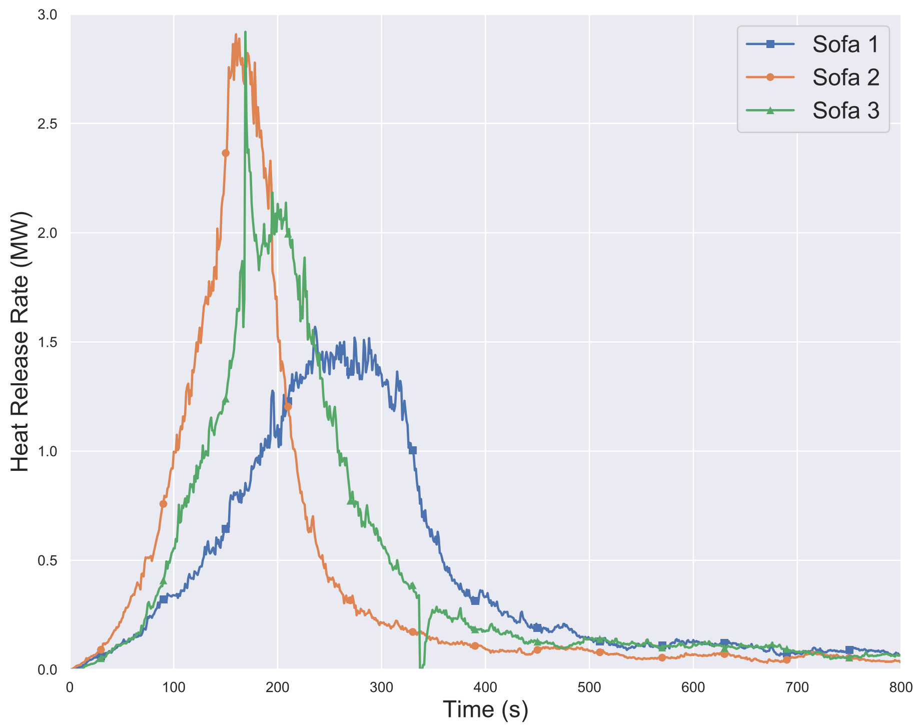


Figure 3.26: Three replicate heat release rate time histories of the sofas used for this experimental series.

Sofa 1 had a peak HRR of 1.6 MW, while the peak HRR for sofa 2 and sofa 3 were both 2.9 MW. Despite the approximate 45% difference in peak heat release values and time-history profile (see Figure 3.26), the total energy released showed similarity (approximately 10% difference, which is within the measurement uncertainty) between all three sofas. Table 3.12 shows the peak HRR and total energy release for each sofa.

Table 3.12: Sofa HRR Data

Sofa #	Peak HRR (MW)	Total Energy Released (MJ)
1	1.6	350
2	2.9	337
3	2.9	357

The beds in each of the bedrooms were similar to one another in construction and material composition. Each bed had a polyurethane foam pad on top of the mattress. The beds were covered with a fitted sheet, a flat sheet and two pillows with pillow cases. In the single story house, the bed assembly was ignited with a small plastic waste container that contained some newspaper. The paper in the waste container was ignited with an electric match. This is the same ignition arrangement used in the heat release rate experiment. The beds in all of the other bedrooms and all those in the two story structure served as target fuels. Table 3.13 shows the peak HRR as well as the total energy released for the three furniture items.

Table 3.13: HRR Data of Upholstered Furnishings Used in the Experiments

Item	Peak HRR (MW)	Total Heat Release (MJ)
Wood Framed Upholstered Chairs	1.0	138
Bed with Bedding	2.1	968

Each of the items used for ignition–the sofa in the living room experiments and the bed with the foam pad and bedding–had a peak HRR with potential to flashover a room as long as there was adequate ventilation to support the combustion. The ignition furniture item along with the other items in the room would provide sufficient fuel for a ventilation-controlled fire environment, which is common in residential structures.

4 Single Story Results

In addition to examining the impact of different ventilation scenarios on the fire environment and the resulting fire damage patterns within the single story structure, the single story experiments were designed to examine the repeatability of a given scenario. Table 4.1 lists the pairs of replicate experiments.

Experiments 1 and 2 (living room), 6 and 8 (kitchen), and 7 and 9 (bedroom 1) were conducted with all of the exterior door and window openings closed for the duration of their respective experiment. The only means for gas transport between the exterior and interior of the structure was through the small gaps around the door and window openings. Keep in mind that at a pressure difference of 10 Pa (0.0014 psi), the single story structure had an estimated equivalent leakage area of 0.08 m^2 (0.9 ft^2).

Experiments 3 and 4 (living room) and 10 and 11 (kitchen) were conducted with the front door open and all of the other exterior door and window openings closed for the duration of the experiments. Experiments 12 and 13 (bedroom 1) were designed to examine the effect of two windows open in the fire room together with the open front doorway. All other exterior door and window openings were closed for the duration of the experiment.

Table 4.1: Experiments in Single Story Structure

Exp #	Fire Location	Ventilation
1	Living Room	All Vents Closed
2	Living Room	All Vents Closed
3	Living Room	Front Door Open
4	Living Room	Front Door Open
5	Living Room	Front Door and Bedroom 3 Window Open
6	Kitchen	All Vents Closed
8	Kitchen	All Vents Closed
10	Kitchen	Front Door Open
11	Kitchen	Front Door Open
7	Bedroom 1	All Vents Closed
9	Bedroom 1	All Vents Closed
12	Bedroom 1	Front Door and Bedroom 1 Windows Open
13	Bedroom 1	Front Door and Bedroom 1 Windows Open

4.1 Living Room Fires

The living room was the room of origin for five of the fire experiments conducted in the single story. Looking in from the front door toward the hallway to the bedrooms, the sofa against the wall to the right of the hallway was the first item ignited in each of these experiments (see Figure 3.18). The point of ignition was the left side of the sofa, at the intersection of the seat cushion, the arm rest, and the back cushion.

The only intended variations between the living room fire experiments (Experiments 1–5) were changes to the structure ventilation. The ventilation conditions were established prior to ignition and maintained throughout the experiment. In the experiments where all of the vents were closed, conditions were monitored post-test to determine if the fire condition would change once additional air was allowed to flow into the structure. Here, post-test is defined as the fire being significantly reduced, no further damage being created or spread, and prior to firefighter intervention.

4.1.1 All Exterior Vents Closed

Experiment 1

The sofa was ignited (t = 0 s) with a remote operated electric match. As the fire grew on the left side of the sofa, a definitive thermal plume formed. As the hot gases reached the ceiling, the plume turned and transitioned into a ceiling jet.

At 40 s after ignition, flames extended past the top of the back of the sofa and began exposing the gypsum board wall. As the fire grew, the ceiling jet spread across the ceiling of the living room and impacted the walls. The hot gas (smoke) layer began to thicken, and the interface between the hot gas layer and the cool layer in the house began to descend. Within 80 s of ignition, the smoke layer was at least 0.4 m (1.3 ft) below the ceiling as smoke flowed into the kitchen, dining room, and bedroom 2 through the open doorways.

The flames from the sofa appear to have reached the ceiling by 120 s after ignition. The hot gas layer continued to develop and it was approximately 0.61 m (2 ft) deep throughout all of the rooms open to the living room. At the same time, light gray smoke was observed exiting the top edges of the front door.

Based on the images from the thermal imaging cameras at 150 s after ignition, the thermal plume had grown to approximately 0.61 m (2 ft) wide at the top of the seat cushion to a narrow section at the section at the ceiling. The plume shape, based on the IR image, was triangular. The hot gas layer/cool air interface dropped to approximately 1.2 m (4 ft) below the ceiling in the living room and the open rooms connected to the living room.

By 180 s after ignition, flashover indicators were observed. Flames from the area of ignition had extended across the ceiling above the ignition sofa, and as a result, the flames on the sofa cushions had spread across the entire width of the seat cushions. In the area of ignition, flames had spread to the floor from polyurethane foam dripping from the burning seat cushion. The hot gas layer had descended to within 0.3 m (1 ft) above the floor throughout all of the rooms open to the living room. The hot gas layer was at the same level in the living room, with the exception of the area between the point of ignition and the front door. In this region of the living room, the hot gas/cool air interface appeared to be approximately 1.2 m (4 ft) above the floor. From the exterior, black colored smoke was observed flowing around the edges of the front door. Some sections had more smoke flow than others. The level of the smoke flow was mainly around the upper 0.9 m (3 ft) of the door. Light gray smoke exited from the upper right side of the living room window shutters. Also, small flames and black smoke flowed out of top edge of the center of the living room window shutters. Plumes of smoke were also observed flowing out of the instrumentation sections of the structure as a result of gas sampling ports, wire penetrations, and electrical outlets.

At 185 s after ignition, the carpeting between the target sofa and the target chairs began to off-gas and ignite. The volume of flames increased. Within the next five seconds, the living room window shutters were pushed outward, enough to allow high velocity flames to burn straight up out of the top gap and straight down out of the bottom gap. These exterior flames continued to burn until 205 s after ignition. During this same period, smoke could be seen flowing around the entire front door, including the gap between the bottom of the door and the threshold. This was an indication that the hot gas layer had finally reached the floor of the living room. Light gray smoke was observed to be leaking out of gaps around the windows of the rooms open to the living room. Inside the living room, some flames could still be seen burning in the furnished area through the smoke. At this point, smoke could be seen entering bedroom 1. Bedroom 1 and bedroom 3 had their doors to the hallway closed.

Within seconds after the exterior flames stopped, evidence of flames in the living room were no longer visible, either in the visual video or the IR video. Temperatures began to decrease in the living room and in all rooms open to the living room. The two closed bedrooms remained at near ambient temperatures.

By 300 s after ignition, the temperatures throughout the structure were approximately 200 °C (390 °F) or less. The fire appeared to have self extinguished. Temperatures continued to decrease, oxygen levels increased, and pressures trended toward atmospheric pressure. Conditions were monitored until 15 min after ignition to ensure sufficient time was allowed for any potential rekindle to occur. The timeline for this experiment is provided in Table 4.2.

Table 4.2: Timeline for Experiment 1, Living Room Fire with All Exterior Vents Closed

Time (s)	Event
0	Ignition on the left side of the sofa
40	Flames extended past the top of the back of the sofa, gypsum board exposed to flame, ceiling jet spread across the living room ceiling, impacting walls, HGL forming
80	Smoke is flowing into the kitchen, dining room, and bedroom 2, HGL has grown to at least 0.4 m below the ceiling
120	Flames from the sofa reach the ceiling, HGL approximately 0.61 m thick is present in all rooms open to the living room, Light gray smoke exiting around the top edges of the front door
150	The thermal plume has grown to approximately 0.61 m wide at the top of the seat cushion extending in a narrow triangle to the ceiling, HGL is approximately 1.2 m below the ceiling in all rooms connected to the fire room
180	Fire in living room transitioning to flashover, HGL descended to within 0.3 m above floor in all areas open to the living room, except HGL between ignition area and front door is approximately 1.2 m above the floor, black smoke flowing around upper edges of front door. Light gray smoke exiting through upper right side of living room window shutters, small flames and black smoke pushing out of top edge of center living room window shutters
185	Carpeting between ignition sofa and adjacent chairs ignites
190	Living room window shutters pushed outward, with high velocity flames burning straight up out of the top gap and straight down out of the bottom gap
200	Smoke flowing around entire front door, including bottom gap, and HGL reaches the floor of the living room. Light gray smoke leaking out of gaps around windows of rooms open to the living room, flames still visible in living room, smoke begins to enter closed bedroom 1
205	Exterior flames stop, flames in living room are no longer visible
300	Fire appears to have self-extinguished
900	Living room shutters opened
962	Front door opened, no active burning

Figure 4.1 displays the time history of the thermocouple temperatures in the living room. The growth of the hot gas layer, starting at the ceiling and descending to within a 0.3 m (1 ft) above the floor occurred for the first 180 seconds. Seconds later, the temperatures rapidly increased to more than 800 °C (1470 °F). Temperatures higher than 600 °C (1112 °F) from ceiling down to the floor would meet the defined conditions for flashover. Within 30 seconds of the transition to flashover, the temperatures in the living had started to decrease. A minute later, the temperatures had all decreased by more than 500 °C (930 °F). The downward trend in temperatures continued until the end of the experiment.

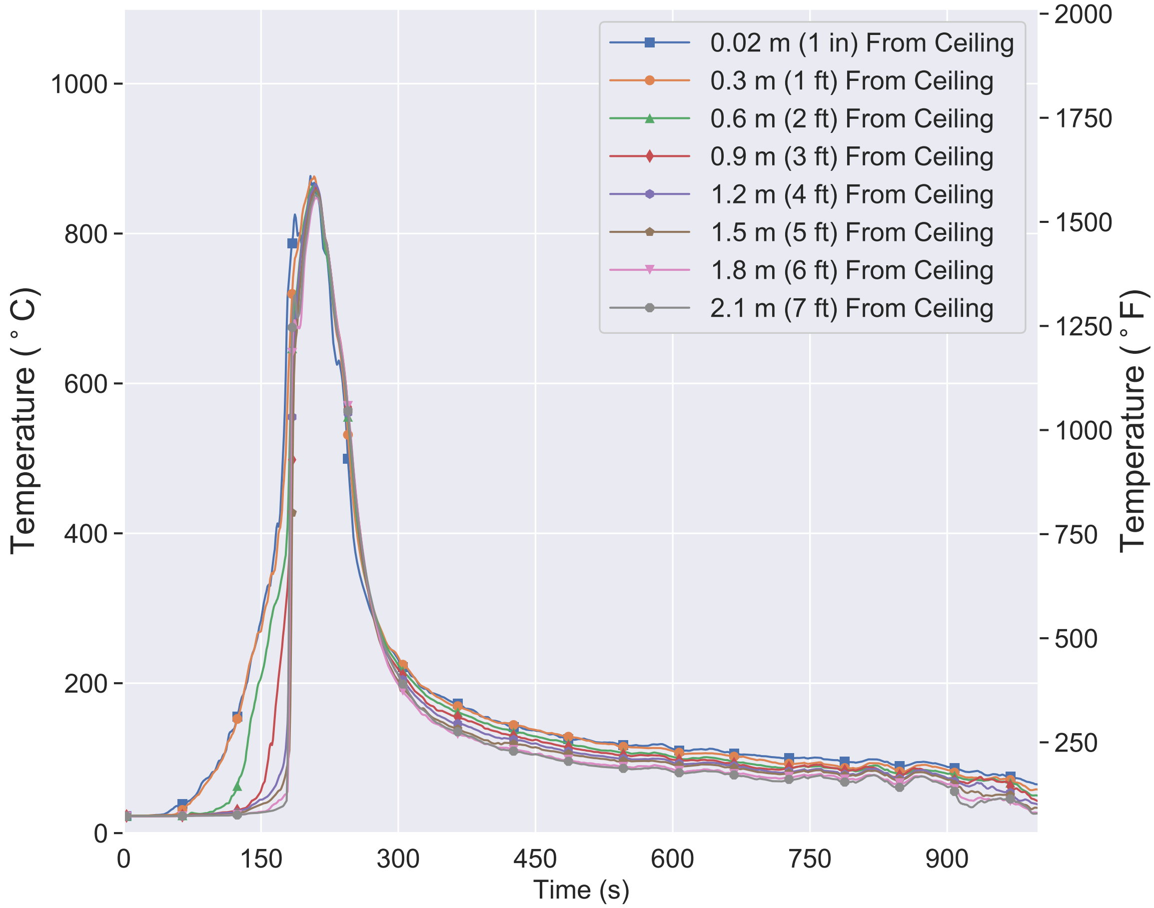
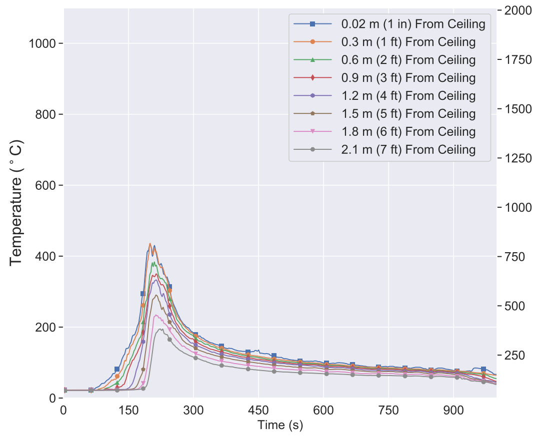
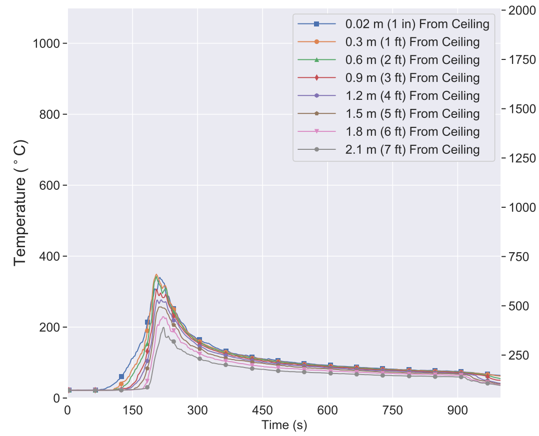


Figure 4.1: Experiment 1, no exterior ventilation openings, living room temperature versus time.

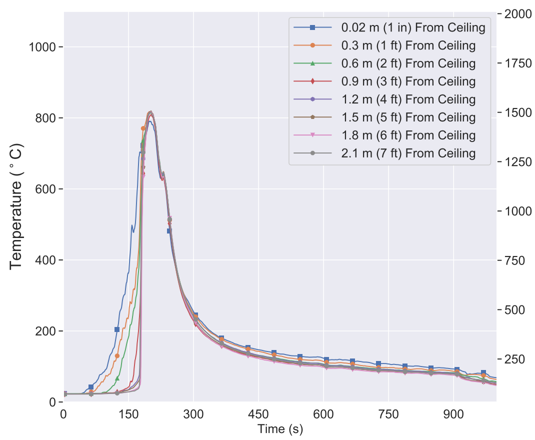
Figure 4.2 shows the temperature histories for all of the other instrument locations in the single story structure. The dining room, kitchen, hallway, and bedroom 2 are areas that were open to the living room, and as a result the temperature trends follow those of the living room. The hallway thermocouple array was located closest to the area of ignition while the bedroom 2, kitchen, and dining room thermocouples were further away. Being remote from the living room resulted in reduced peak temperatures. Only the hallway exceeded 600 °C (1112 °F) from ceiling down to the floor. The other rooms did not transition through flashover. The bedroom furniture in bedroom 2 did not ignite. The temperatures in the bedrooms with closed doors did not increase significantly.



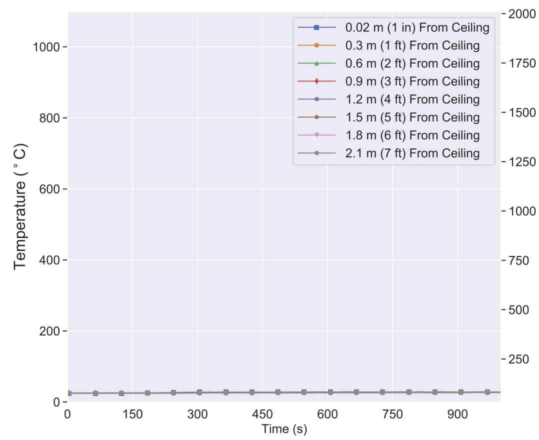
(a) Dining Room Temperature



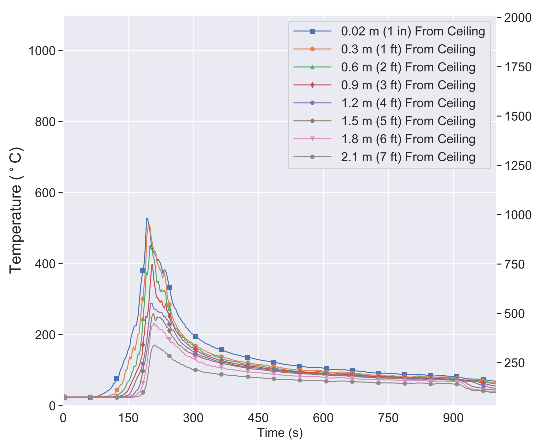
(b) Kitchen Temperature



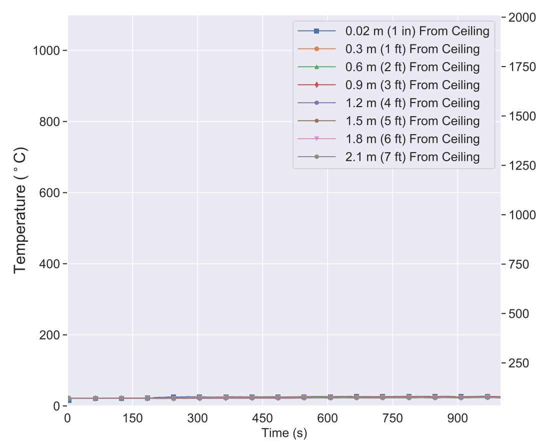
(c) Hallway Temperature



(d) Bedroom 1 Temperature



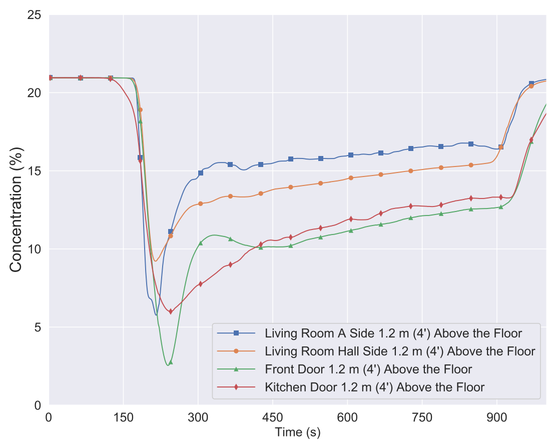
(e) Bedroom 2 Temperature



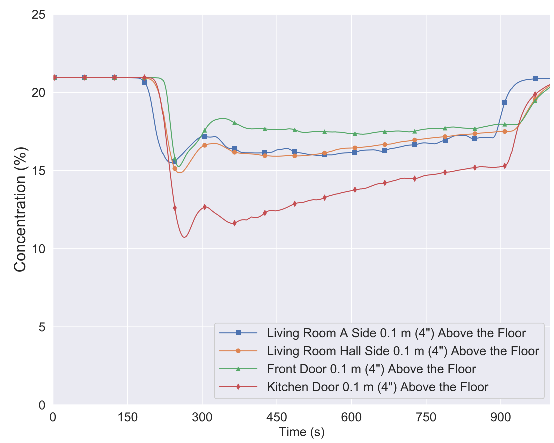
(f) Bedroom 3 Temperature

Figure 4.2: Experiment 1, no exterior ventilation openings, temperature time histories for all of the rooms.

Figure 4.3 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the point of ignition. Four of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.3a), and the other four were positioned under the upper sampling ports and 100 mm (4 in.)above the floor (see Figure 4.3b). The four meter sampling from 1.2 m (4 ft) above the floor measure a decrease in oxygen as soon as the hot gas layer covered the sampling port. The oxygen meters measuring conditions to the right of the ignition sofa exhibited the earliest decrease at each level, which started at approximately 125 seconds and 175 seconds after ignition for the 1.2 m (4 ft) and the 100 mm (4 in.), respectively. The remaining 1.2 m (4 ft) oxygen meters registered decreased oxygen concentrations starting at approximately 170 seconds after ignition. The oxygen meters that measured gases sampled at 1.2 m (4 ft) above the floor had oxygen concentrations of 10% or less. The oxygen meters that measured gases sampled at 100 mm (4 in.) had oxygen concentrations of approximately 15%.



(a) Oxygen at 1.2 m Above Floor



(b) Oxygen at 0.1 m Above Floor

Figure 4.3: Experiment 1, no exterior ventilation openings, oxygen concentration versus time.

Figure 4.4 shows the hallway velocity probes. The velocity profile indicates that flow is initially all towards the bedroom, which corresponds to the living room fire growth with peak values of approximately 2 m/s (4.5 mph). At peak flow down the hallway, there was also backflow near the bottom of the hallway of 1 m/s (2.25 mph) as combustion products displayed the air in the open bedroom.

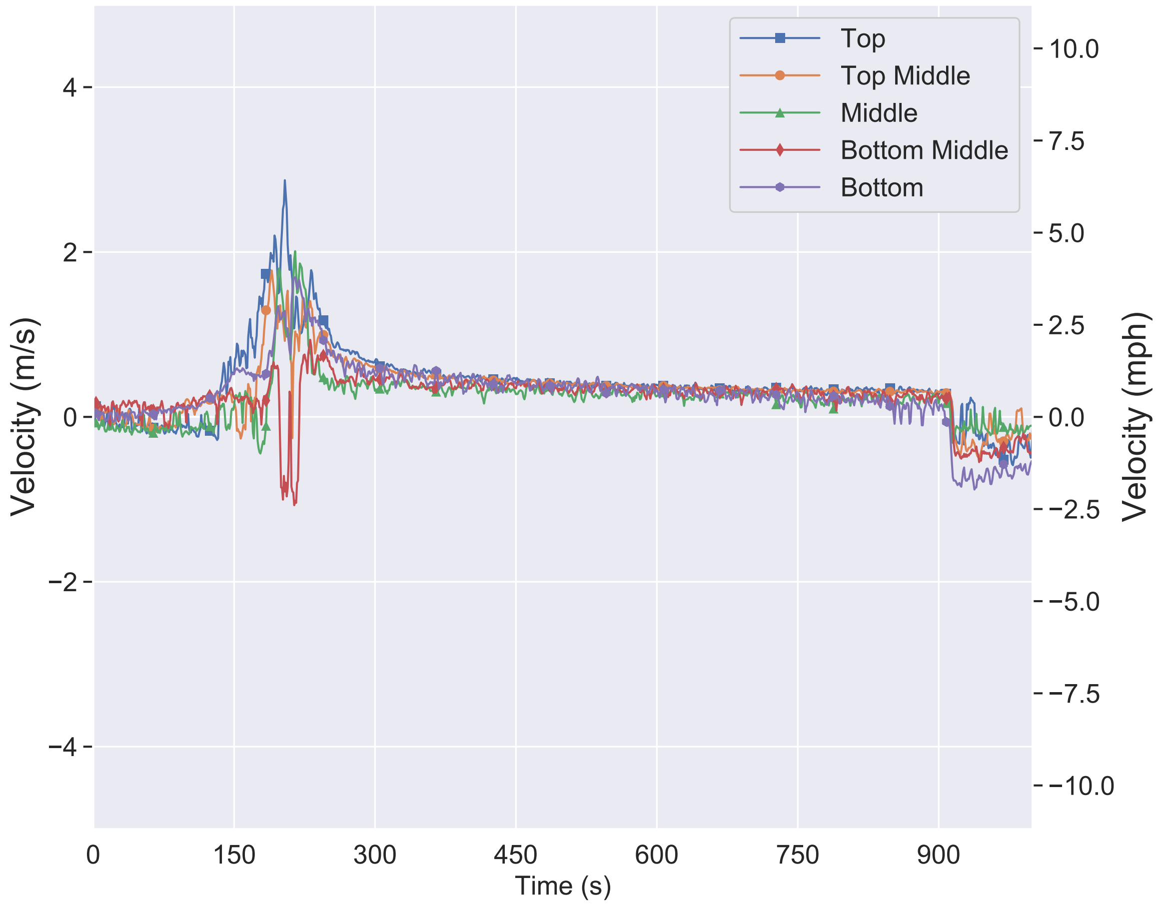
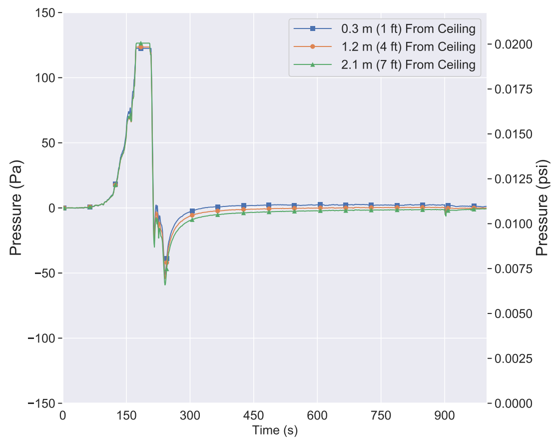
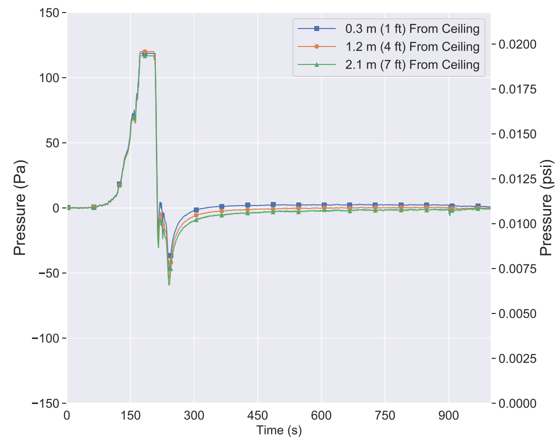


Figure 4.4: Experiment 1, no exterior ventilation openings, hallway velocity versus time. Positive velocity indicated by flow from living room toward bedroom 2.

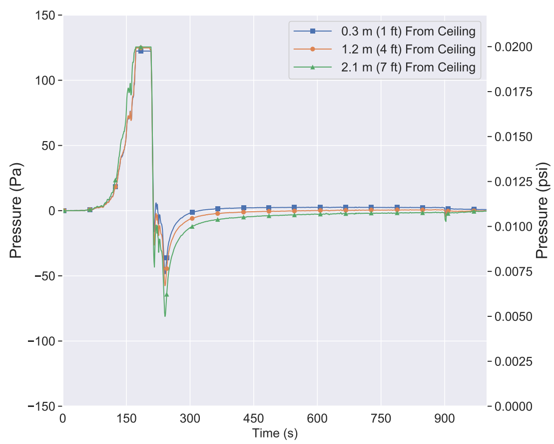
Figure 4.5 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. The rooms open to the living room had similar pressures. As flashover began, the pressure increased and exceeded the 125 Pa limit of the pressure sensors. As the flaming combustion ceased due to a lack of sufficient oxygen for combustion, and the gas temperatures decreased, the pressures also decreased. In fact, the pressures inside the structure decreased below the atmospheric pressure outside the structure. The combustion seemed to cycle once (i.e., increase then cease), and after that the pressure tended toward equalizing with the atmospheric pressure. The two bedrooms with closed doors were also impacted by the pressure increase but to a lesser amount. During the rapid pressure increase, smoke was pushed in to bedrooms 1 and 3, which in turn may have allowed fresh air to move in to the hallway and to the living room. This may have provided the oxygen for the combustion after the first large pressure drop.



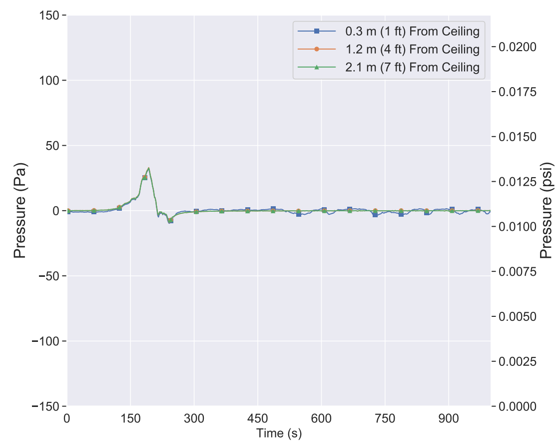
(a) Dining Room Pressure



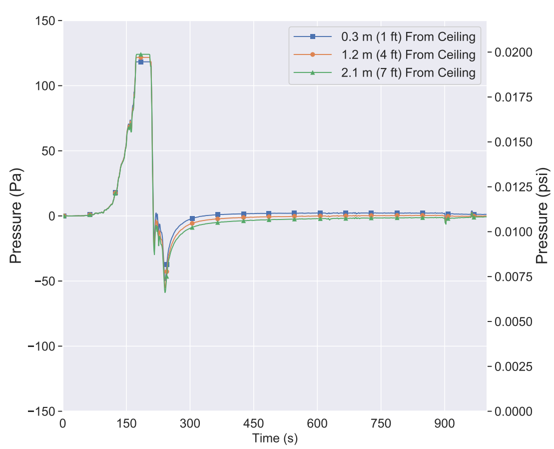
(b) Kitchen Pressure



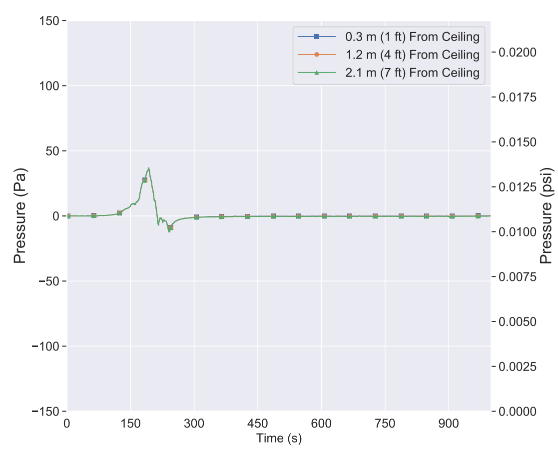
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.5: Experiment 1, no exterior ventilation openings, pressures in all rooms.

Experiment 2

Similar to Experiment 1, the sofa was ignited (t = 0 s) with a remote operated electric match. The fire grew on the left side of the sofa, and a definitive thermal plume formed. As the hot gases reached the ceiling, the plume turned and transitioned into a ceiling jet. The initial fire growth was slower than that of Experiment 1. It took 60 s for the flames to extend past the top of the sofa, 20 s slower than in Experiment 1. Within 120 s after ignition, the flames from the sofa reached the ceiling. The hot gas layer continued to develop. Light gray, translucent smoke flowed into the kitchen.

Thirty seconds later, the living room hot gas layer had a depth of approximately 0.6 m (2 ft). No smoke was observed exiting to the exterior at this time. By 180 s after ignition, polyurethane foam melted and dropped down from the sofa cushions to the floor below the seat cushion that was first ignited. The hot gas layer was observed to be approximately 0.91 m (3 ft) deep in the living room and throughout all of the rooms open to the living room. Light gray smoke was observed exiting the top edges of the front door.

Based on the images from the thermal imaging cameras at 210 s after ignition, the base of the fire had grown to involve approximately half of the seat cushion area. The thermal plume narrowed down as it extended toward the ceiling. The plume shape, based on the IR image, was triangular. The hot gas layer/cool air interface had dropped to approximately 1.2 m (4 ft) below the ceiling in the living room and the open rooms connected to the living room.

At 240 s after ignition, flames had spread to involve the entire width of the sofa seat cushions. The hot gas layer had descended toward the floor. Smoke exited the structure from the gaps along the upper half of the door and along the top and left edges of the living room shutter.

Seconds later, jet flames were visible exiting out of gaps at the top and bottom of the living room window shutters. The exterior flames continued for about 15 s. During this same period, smoke could be seen flowing around the entire front door, including the gap between the bottom of the door and the threshold.

The majority of smoke flow around the door and out of the gaps around the window shutters had stopped by 275 s after ignition. No visible fire was seen after this time. Smoke continued to exit the structure. The living room window shutters were opened 15 min after ignition. About one minute later, firefighters entered the structure and used a fire extinguisher to suppress a small fire on and under the sofa frame.

Table 4.3: Timeline for Experiment 2, Living Room Fire with All Exterior Vents Closed

Time (s)	Event
0	Ignition on the left side of the sofa
60	Flames extended past the top of the back of the sofa, gypsum board exposed to flame
120	Flames from the sofa reach the ceiling, HGL developing, light gray smoke flowing into kitchen
150	Hot gas layer in living room is approximately 0.6 m below ceiling, no smoke exiting to the exterior
180	Material from sofa cushion is melting and dripping to floor, HGL is approximately 0.9 m thick in living room and rooms open to living room, light gray smoke exiting top edges of the front door
210	The base of the fire has grown to involve approximately half of the seat cushion area extending in a narrow triangle to the ceiling, HGL has dropped to approximately 1.2 m below the ceiling in living room and all open connected rooms
240	Flashover transition has started, flames spread to involve the entire width of sofa seat cushions and are flowing across living room ceiling, HGL has descended near the floor in all areas open to the living room (except HGL) between ignition area and front door is approximately 1.2 m above the floor, smoke exiting structure from gaps along the upper half of front door and along top and left edges of living room window shutter
243	Flames exiting out of gaps at the top and bottom of living room window shutters, smoke flowing around entire front door, including bottom gap
260	Exterior flames stop
275	Smoke flow around the door and out of the gaps around the window shutters has stopped, fire is no longer visible
900	Living room window shutters opened
975	Firefighters enter front door, extinguish small fire burning on and under the sofa frame

Figure 4.6 displays the time history of the thermocouple temperatures in the living room. The growth of the hot gas layer, starting at the ceiling and descending to within a 0.3 m (1 ft) above the floor, occurred for the first 220 s. Seconds later, the temperatures of the thermocouples closest to the floor rapidly increased to more than 800 °C (1470 °F). Temperatures higher than 600 °C (1112 °F) from ceiling down to the floor would meet the defined conditions for flashover. Within 40 s of the transition to flashover, the temperatures in the living room started to decrease. One minute later, the temperatures had all decreased by more than 400 °C (750 °F). The downward trend in temperatures continued until the end of the experiment. The trend of the temperatures was similar to Experiment 1.

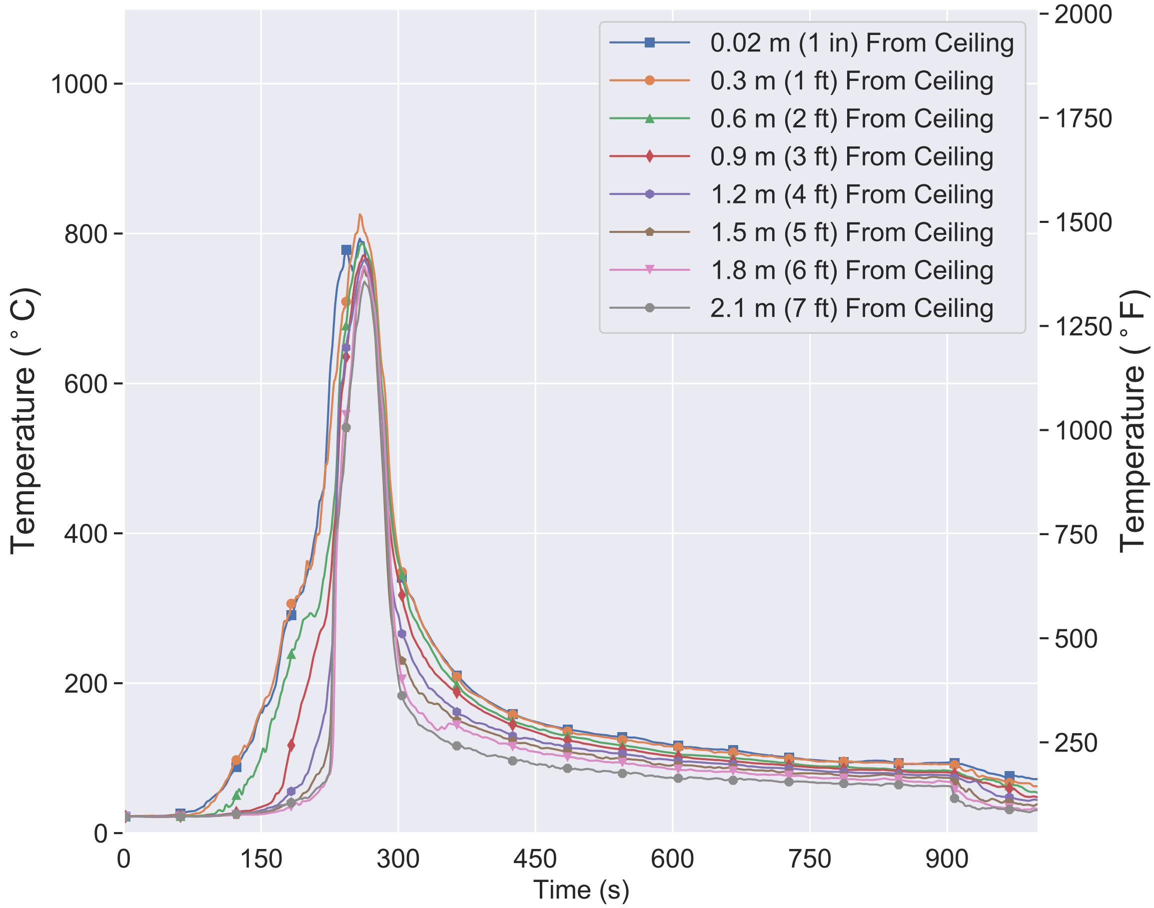
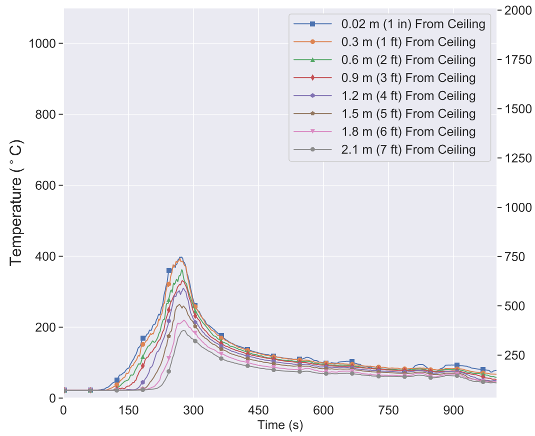
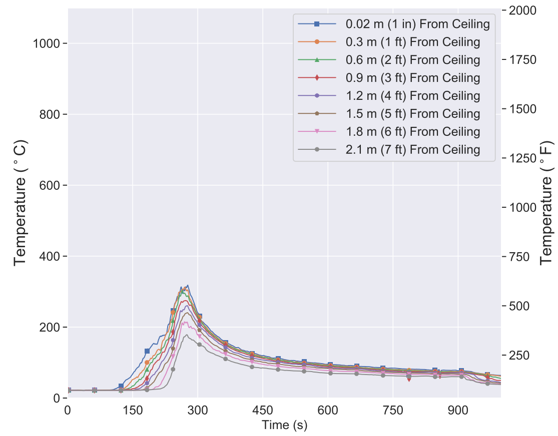


Figure 4.6: Experiment 2, no exterior ventilation openings, living room temperature versus time.

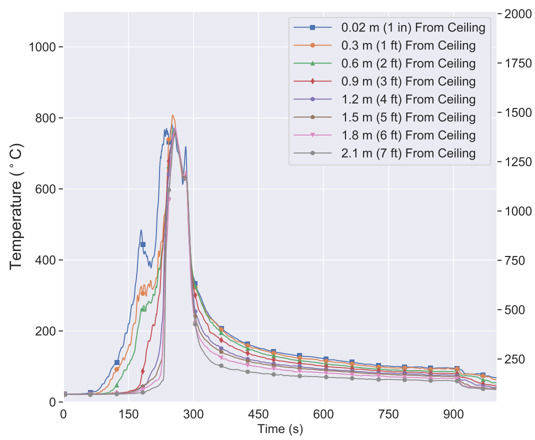
Figure 4.7 shows the temperature histories for all of the other thermocouple array locations inside the single story structure. The dining room, kitchen, hallway, and bedroom 2 were open to the living room, and as a result the temperature trends follow those of the living room. The hallway thermocouple array was located closest to the area of ignition while the bedroom 2, kitchen, and dining room thermocouples were further away. Being remote from the living room resulted in reduced peak temperatures. Only the hallway exceeded 600 °C (1112 °F) from ceiling down to the floor. The other rooms did not transition through flashover. The bedroom furniture in bedroom 2 did not ignite. The temperatures in the bedrooms with closed doors did not increase.



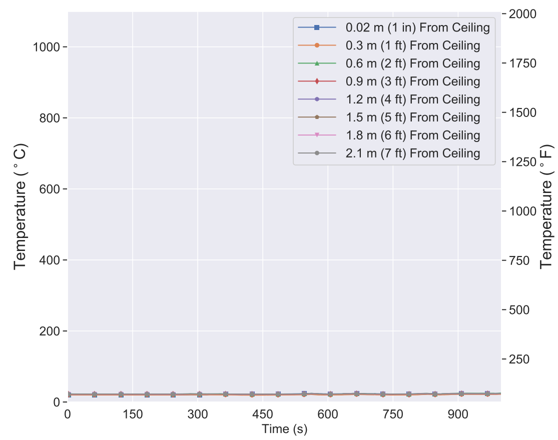
(a) Dining Room Temperature



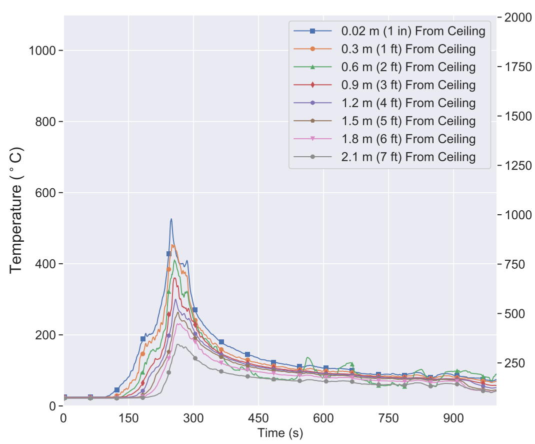
(b) Kitchen Temperature



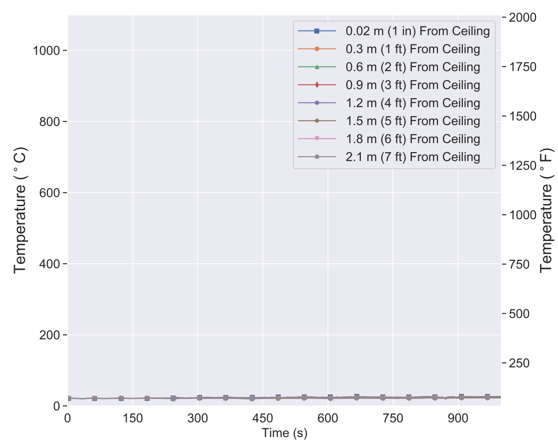
(c) Hallway Temperature



(d) Bedroom 1 Temperature



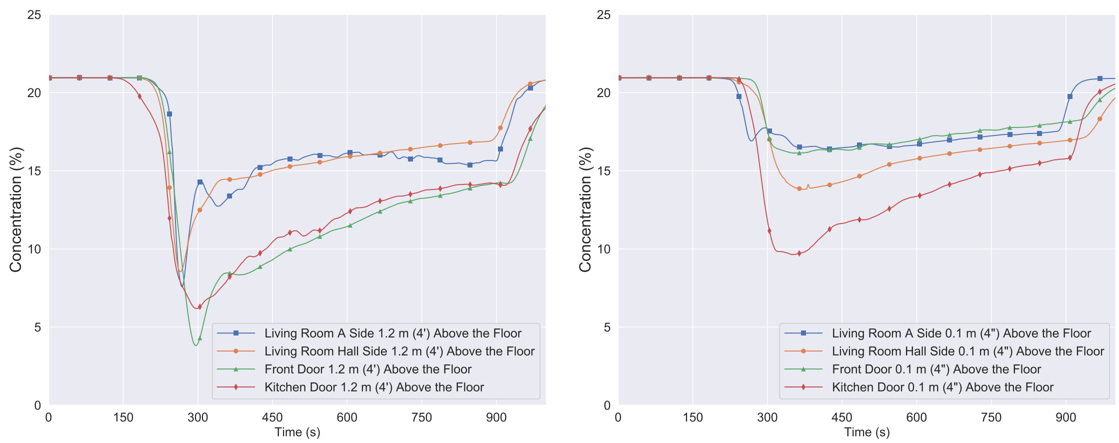
(e) Bedroom 2 Temperature



(f) Bedroom 3 Temperature

Figure 4.7: Experiment 2, no exterior ventilation openings, time-temperature histories for all of the rooms.

Figure 4.8 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the point of ignition. Four of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.3a) and the other four were positioned under the upper sampling ports and 100 mm (4 in.) above the floor (see Figure 4.3b). The four meter sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port. The oxygen meters measuring conditions to the right of the ignition sofa exhibited the earliest decrease at each level, which started at approximately 135 s and 225 s after ignition for the 1.2 m (4 ft) and the 100 mm (4 in.), respectively. The remaining 1.2 m (4 ft) oxygen meters registered decreased oxygen concentrations starting at approximately 185 s after ignition. The oxygen meters that measured gases sampled at 1.2 m (4 ft) above the floor had minimum oxygen concentrations of less than 10%. The oxygen meters that measured gases sampled at 100 mm (4 in.) had minimum oxygen concentrations of 16.4% or less.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.8: Experiment 2, no exterior ventilation openings, oxygen concentration versus time.

Figure 4.9 shows the hallway velocity probes. The velocity profile indicates flow is initially all towards the bedroom, which corresponds to the living room fire growth with peak values of approximately 2 m/s (4.5 mph). At peak flow down the hallway, there was also backflow near the bottom of the hallway of 1 m/s (2.25 mph) as combustion products displayed the air in the open bedroom.

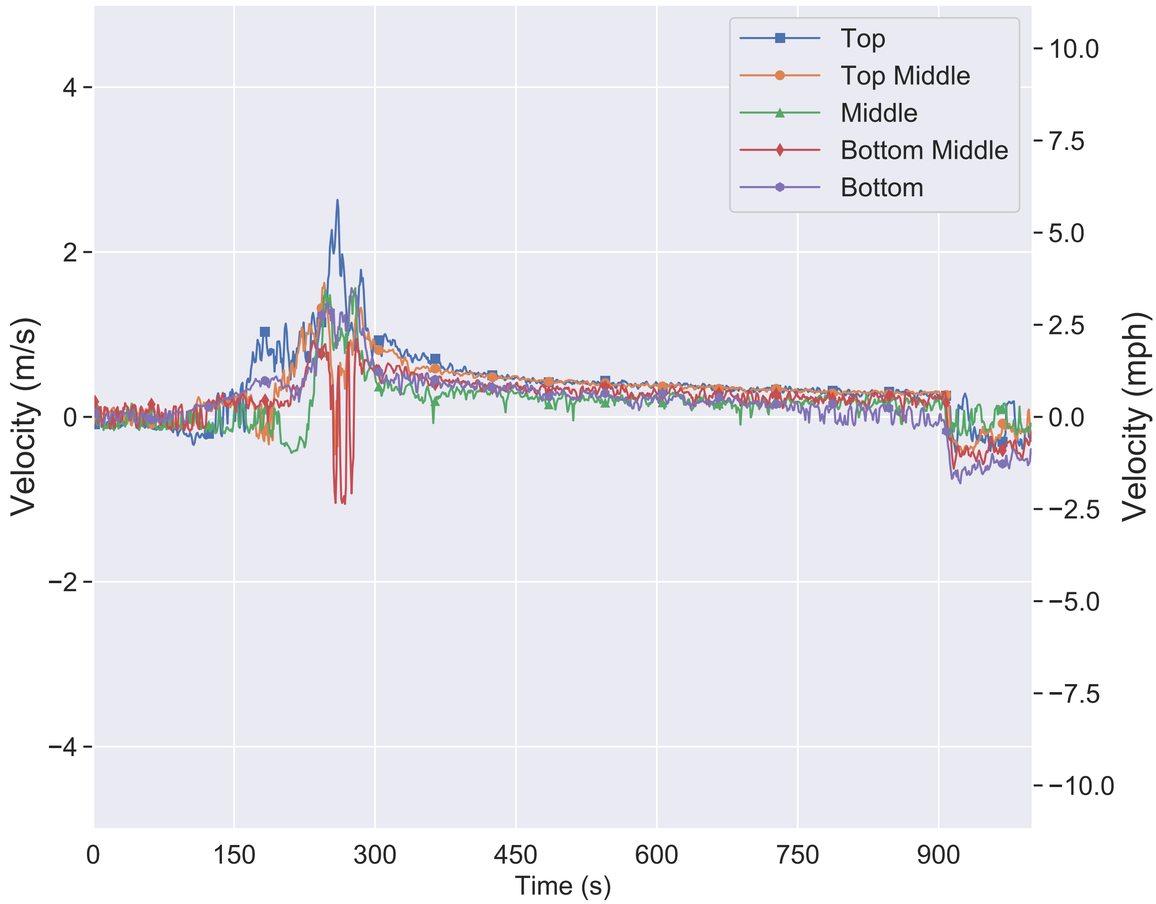
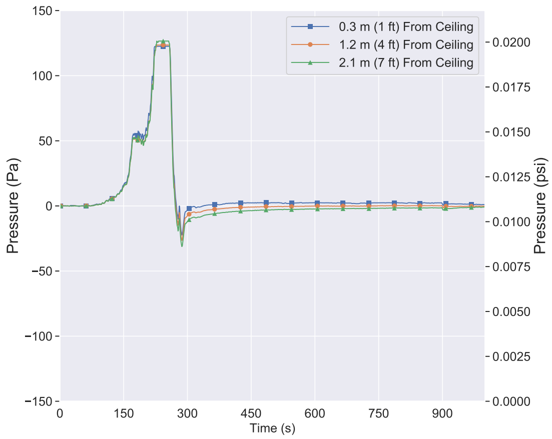
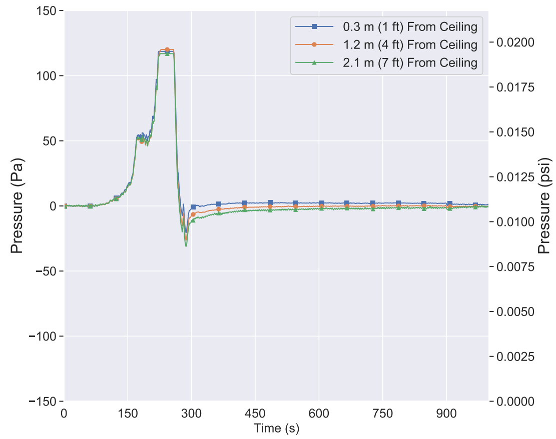


Figure 4.9: Experiment 2, no exterior ventilation openings, hallway velocity versus time.

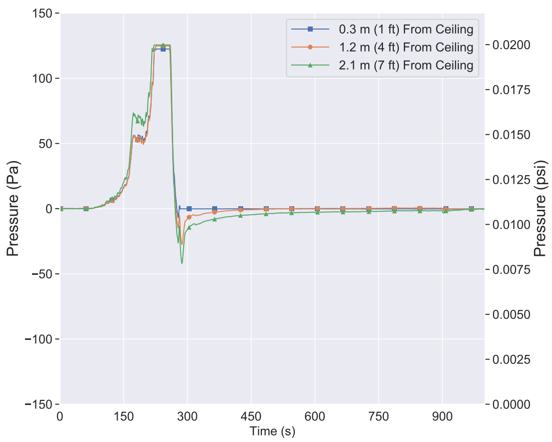
Figure 4.10 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. The rooms open to the living room had similar pressures. As flashover began, the pressure increased and exceeded the 125 Pa limit of the pressure sensors. As the flaming combustion ceased due to a lack of sufficient oxygen for combustion, and the gas temperatures decreased, the pressures also decreased. The pressures inside the structure decreased below the atmospheric pressure outside the structure. The combustion seemed to cycle briefly (i.e., increase then decease), but after that the pressure tended toward equalizing with the atmospheric pressure as smoke slowly leaked out of the structure and was replaced by air. The two bedrooms with closed doors were also impacted by the pressure increase but to a lesser amount. During the rapid pressure increase, smoke was pushed in to bedrooms 1 and 3, which in turn may have allowed fresh air to move into the hallway and to the living room. This may have provided the oxygen for the combustion after the first large pressure drop.



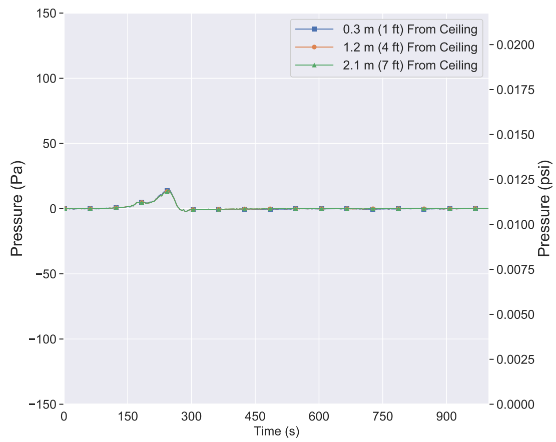
(a) Dining Room Pressure



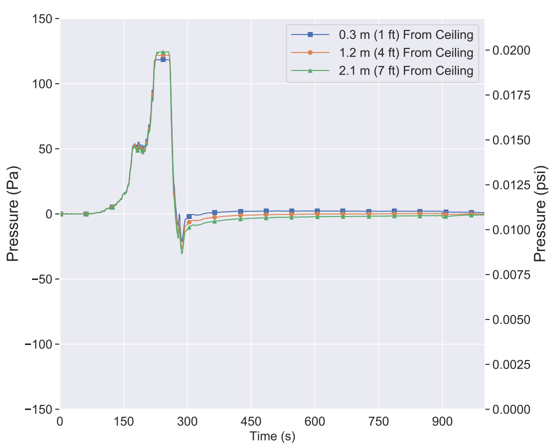
(b) Kitchen Pressure



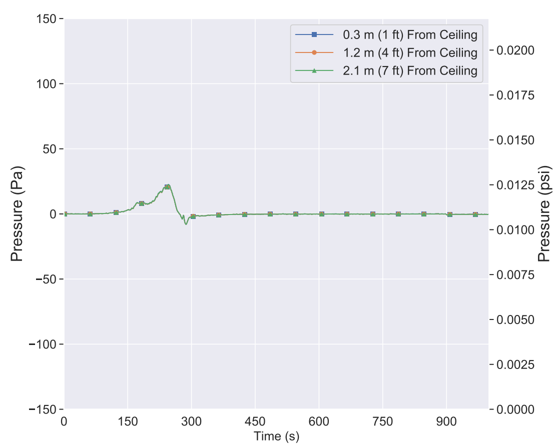
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.10: Experiment 2, no exterior ventilation openings, pressures in all rooms.

4.1.2 Front Door Open

Experiments 3 and 4 were designed to be similar to Experiments 1 and 2, except for one change in ventilation, an open front door. The front door was open for the duration of Experiments 3 and 4. All of the other exterior vents remained closed.

Experiment 3

Similar to Experiments 1 and 2, the sofa was ignited (t = 0 s) with a remotely operated electric match. The ignition location was also similar. The fire grew on the left side of the sofa, and a definitive thermal plume formed. As the hot gases reached the ceiling, the plume turned and transitioned into a ceiling jet. It took 40 s for the flames to extend past the top of the sofa, similar to Experiment 1 and 20 s faster than Experiment 2.

Smoke was observed flowing out of the open front door within 90 s after ignition. Within the next minute, the flames had reached the ceiling above the area of ignition and the hot gas layer interface had descended to approximately 0.91 m (3 ft) below the ceiling. Smoke had also flowed into the open rooms adjacent to the living room at this time.

By 150 s after ignition, the base of the fire was about 0.6 m (2 ft) wide. Thermal imaging provided a triangular shaped heat signature from the base of the fire on the seat cushion to a point at the ceiling. Polyurethane foam from the area of ignition was melting, dripping, and burning on the carpeting at 180 s after ignition. Smoke flowed out of the top quarter of the open front doorway.

As the fire increased in size, the flames spread across the ceiling and across the top of the sofa seat cushions, extending across the full width of the sofa by 210 s after ignition. Seconds later flames extended out of the open front doorway and the exiting smoke filled the upper half of the doorway. The transition through flashover was completed by 240 s after ignition. The fire was allowed to burn for 6 min post-flashover. During the post-flashover burning period, several notable changes in the appearance of the fire occurred. The experiment timeline appears in Table 4.4.

Table 4.4: Timeline for Experiment 3, Living Room Fire with Front Door Open

Time (s)	Event
0	Ignition on the left side of the sofa
40	Flames extended past the top of the back of the sofa, gypsum board exposed to flame
90	Smoke flowing out the open front door
135	Flames reached ceiling above ignition area, HGL is approximately 0.9 m below the ceiling, smoke is spreading into open adjacent rooms
150	The base of the flame has grown to approximately 0.6 m wide at the top of the seat cushion, extending in a narrow triangle to the ceiling
180	Material from ignition sofa cushion is melting, dripping, and burning on the carpeting, smoke flowing out the upper quarter of the open front doorway
210	Flashover transition has started, flames spread across the living room ceiling and across the top of the sofa (involving the entire width of the seat cushions), flames reach the open front doorway with smoke filling the upper half of the doorway
240	Living room fire fully developed
255	Flames exiting the front door become sooty and dark
350	Soot is gone and clean burning flames fill the front doorway
420	Flames become sooty again, flames and smoke exiting the upper half of the front doorway
625	Flames can be seen on living room floor, second sofa, and chairs, living room window shutters opened, flames extend out of open window
630	Fire suppression started with hose stream through open living room window

The thermal image capturing the wall area located about a 0.5 m to the left of the area of origin displayed an interesting trend. As the living room was transitioning to flashover (see Figure 4.11), the temperature and color signatures indicated a rapid rate of increase. Seconds after flashover had occurred, the wall area had cooled down to less then 150 °C (300 °F) while the gas temperatures in the center of the living room were approximately 1000 °C (1832 °F) from the ceiling down to the floor. The temperature and color signatures remained at the lower energy levels until the transition in flaming at the front door. Once the clean burning at the front doorway began, the temperatures near the area of origin began to increase again.

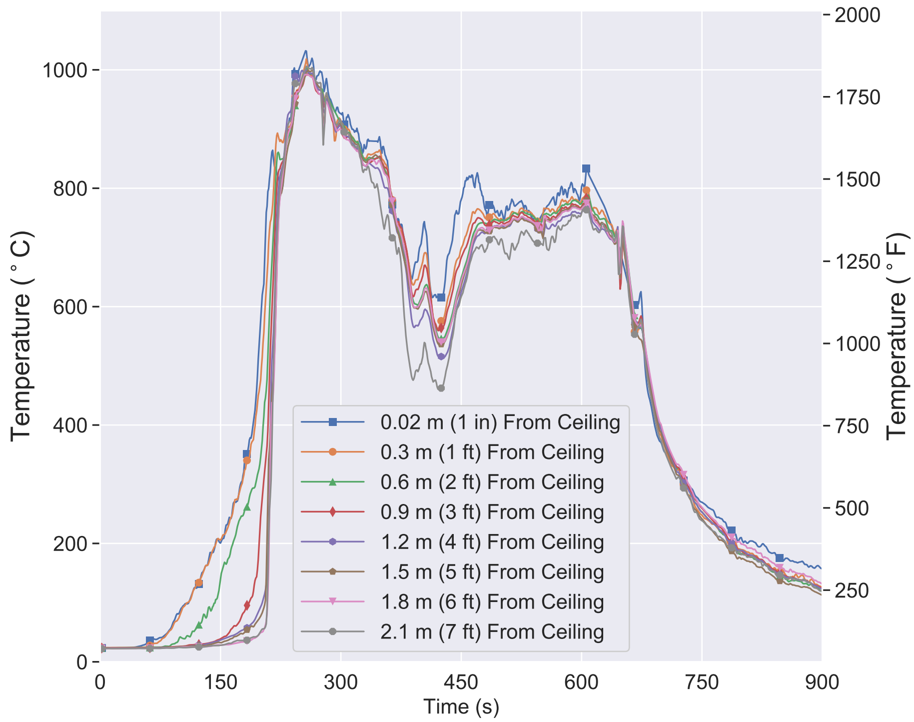


Figure 4.11: Experiment 3, front door open, living room temperature versus time.

The flames exiting the front door changed after flashover (see Figure 4.12). Initially the flames became sooty and dark. Then approximately 2 min post-flashover the soot was gone and clean burning flames filled the doorway. This clean burning lasted for a little more than 1 min, then the soot returned to the flames. The doorway returned to being a bi-directional vent, with the flames and smoke exiting the upper half of the doorway and the lower half entraining fresh air.

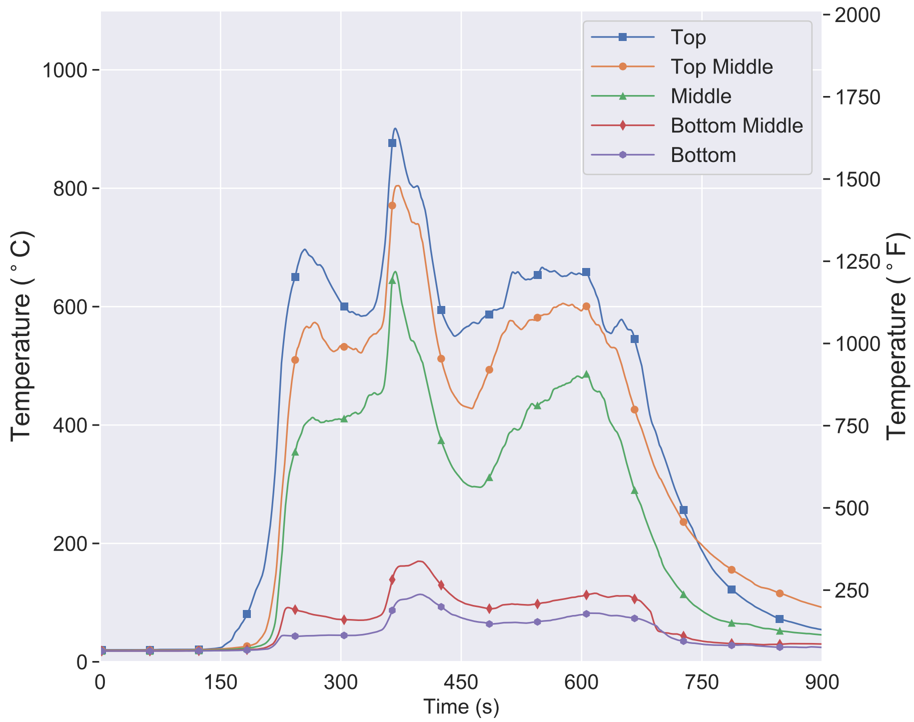
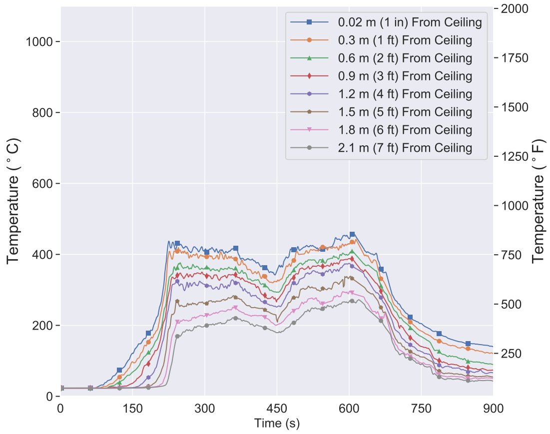
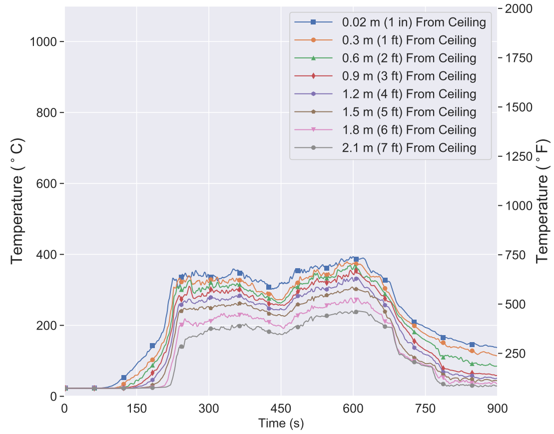


Figure 4.12: Experiment 3, front door open, front door temperatures versus time.

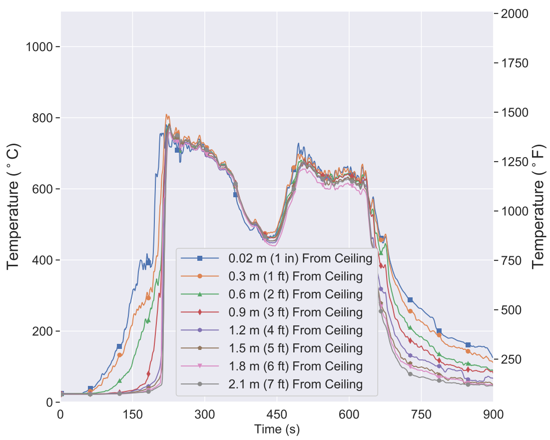
Figure 4.13 shows the temperature histories for all of the other thermocouple array locations inside the single story structure. The dining room, kitchen, hallway, and bedroom 2 areas were open to the living room, and as a result the temperature trends follow those of the living room. The hallway thermocouple array was located the closest to the area of ignition, while the bedroom 2, kitchen, and dining room thermocouples were further away. Being remote from the living room resulted in reduced peak temperatures. Only the hallway exceeded 600 °C (1112 °F) from ceiling down to the floor. The other rooms did not transition through flashover. The bedroom furniture in bedroom 2 did not ignite. The temperatures in the bedrooms with closed doors did not increase.



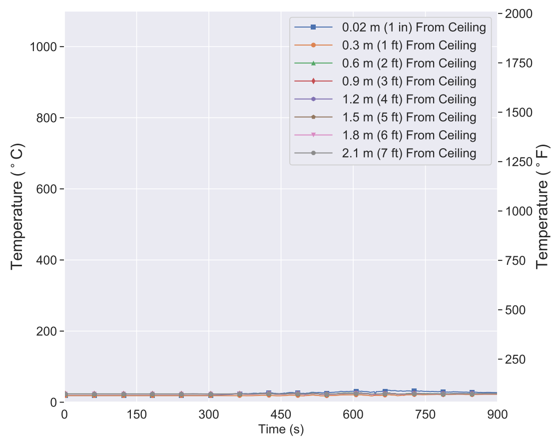
(a) Dining Room Temperature



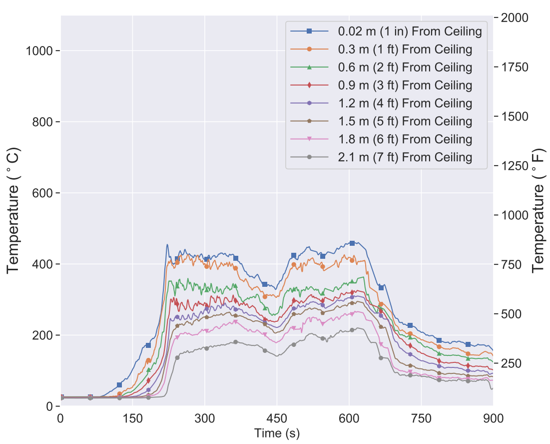
(b) Kitchen Temperature



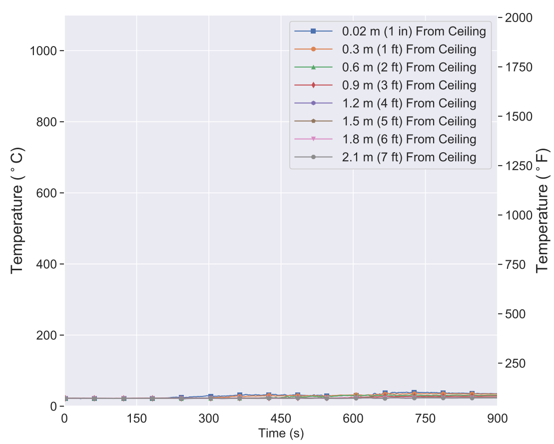
(c) Hallway Temperature



(d) Bedroom 1 Temperature



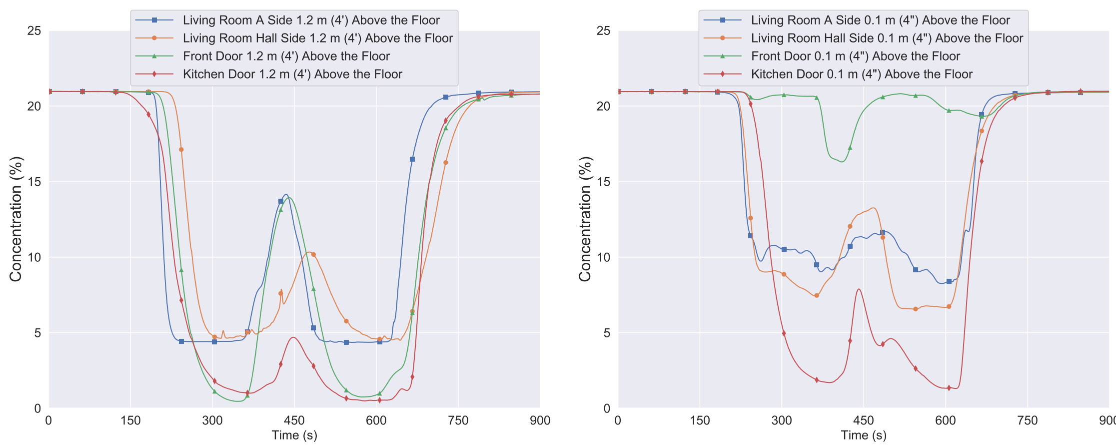
(e) Bedroom 2 Temperature



(f) Bedroom 3 Temperature

Figure 4.13: Experiment 3, front door open, time-temperature histories for all of the rooms.

Figure 4.14 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the point of ignition. Four of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.14a) and the other four were positioned under the upper sampling ports and 100 mm (4 in.) above the floor (see Figure 4.14b). The four meters sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port. The oxygen meters measuring conditions to the right of the ignition sofa exhibited the earliest decrease at each level, which started at approximately 150 s and 230 s after ignition for the 1.2 m (4 ft) and the 100 mm (4 in.), respectively. An important trend to recognize is the initial drop in oxygen at all sensor locations, the subsequent rise in oxygen at approximately 360 s, and the second drop in oxygen concentration at approximately 450 s. The first minimum value in oxygen corresponds to the drop in temperature. A lack of oxygen in the structure limited combustion, and therefore temperatures decreased. As combustion products exited the structure through the top of open front door, oxygen returned through the bottom portion of the doorway as seen by the rise in oxygen reaching a local peak at approximately 450 s. At this point, oxygen returned to levels to support combustion. The result was a second spike in temperature and subsequent drop in oxygen.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.14: Experiment 3, front door open, oxygen concentration versus time.

During the initial fire growth and subsequent temperature rise in the living room, Figure 4.11, the velocity profile at the front door shows the door was a unidirectional exhaust vent (see Figure 4.15). As the fire started to decay due to drop in oxygen concentration, the doorway velocity profile changed to a bi-directional flow with the bottom two probes indicating air flowed into the structure.

The velocity profile in the bedroom hall (see Figure 4.16) shows the gas flow in the upper portion of the hall moving towards the bedrooms while the bottom probe indicates flow moving towards the fire. This circulation worked to exchange the fresh air in the open bedroom with combustion products and move the air toward the seat of the fire. Note the slower circulation velocity between the fire room and the bedroom compared with the higher velocities in the flows between the fire room and the open doorway.

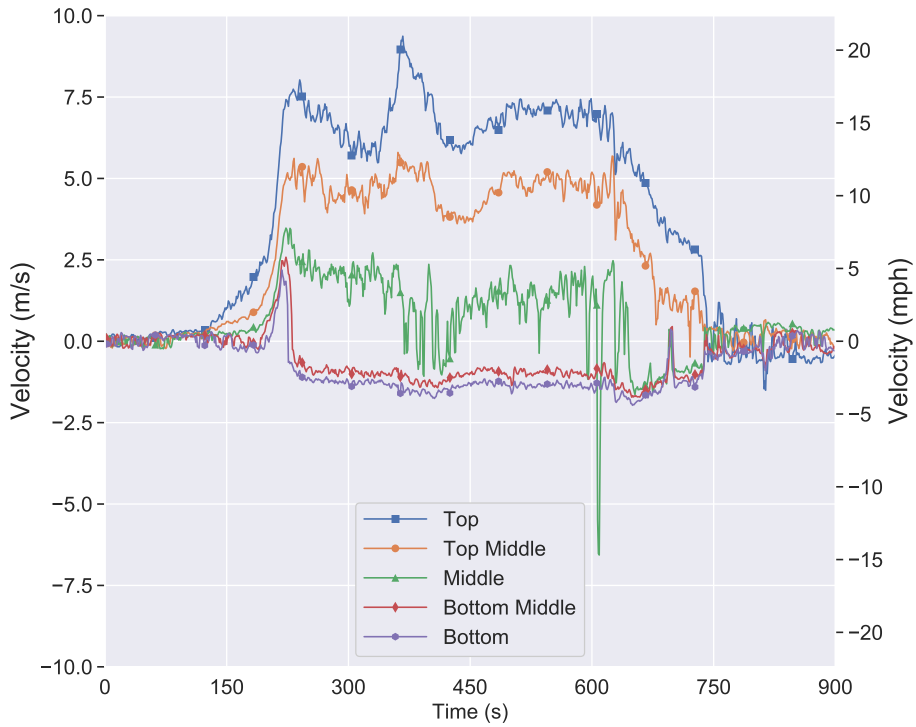


Figure 4.15: Experiment 3, front door open, front door velocity versus time.

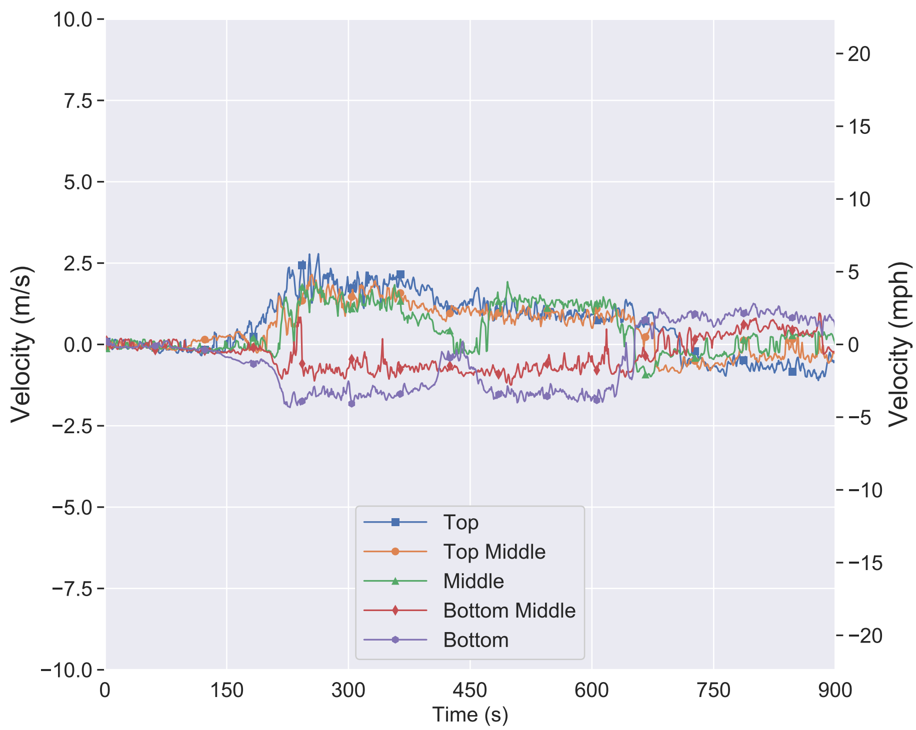
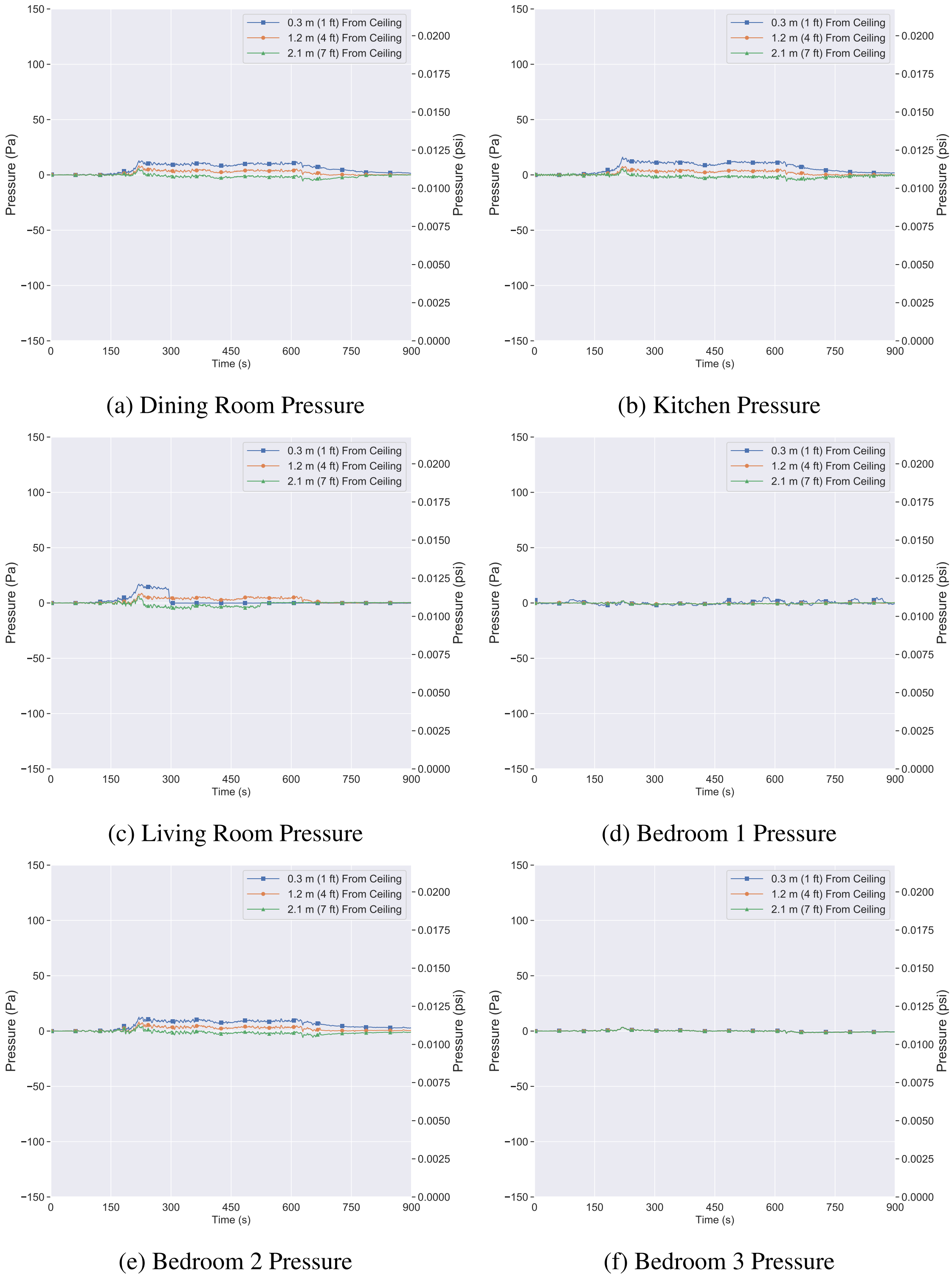


Figure 4.16: Experiment 3, front door open, hallway velocity versus time.

Figure 4.17 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. Unlike Experiments 1 and 2, pressures within the structure did not exceed 20 Pa because of the open front door. The rooms open to the living room had similar pressures. The two bedrooms with closed doors showed minimal pressure change.



(a) Dining Room Pressure

(b) Kitchen Pressure

(c) Living Room Pressure

(d) Bedroom 1 Pressure

(e) Bedroom 2 Pressure

(f) Bedroom 3 Pressure

Figure 4.17: Experiment 3, Front door open, pressures in all rooms.

Experiment 4

Similar to the first three living room experiments, the sofa was ignited (t = 0 s) with a remotely operated electric match in the left corner of sofa. The fire grew on the left side of the sofa, and a definitive thermal plume formed. However, in this fire the flames reached the top of the sofa within 25 s of ignition. Further, the flames appeared to stay limited to the left portion of the sofa and did not spread across the top of the seat cushions as had occurred in the first three experiments. In this experiment, the flames spread under and across the back of sofa. This resulted in hot gases and flames against the wall behind the sofa. Flames began to roll the ceiling at 180 s after ignition. Fifteen seconds later, flames extended out the front door. Flashover occurred at approximately 200 s after ignition. The fire was allowed to burn for 6 min and 50 s post-flashover. As with previous experiments, the post-flashover burning period yielded notable changes in the appearance of the fire.

Initially, flames exiting the front door after flashover were shrouded in unburned soot. Approximately 90 s post-flashover the soot was gone and clean burning flames filled the doorway. This clean burning lasted for slightly longer than 30 s. Soot then returned to the flames. The doorway returned to being a bi-directional vent, with flames and smoke exiting the upper half of the doorway and fresh air being entrained through the lower half. At 260 s post flashover, flames at the door and inside the room appeared to burn without unburned soot. This condition maintained itself until suppression at 10 min and 10 s after ignition. The thermal image capturing the wall area located about 0.5 m to the left of the area of origin displayed trends similar to the previous experiment. Table 4.5 provides a timeline of events.

Table 4.5: Timeline for Experiment 4, Living Room Fire with Front Door Open

Time (s)	Event
0	Ignition on the left side of the sofa
25	Flames extended past the top of the back of the sofa, gypsum board exposed to flame
60	Flames approximately 1.2 m above sofa seat, ceiling jet moving smoke across the living room ceiling, light gray smoke exiting front doorway
120	Horizontal flame spread along arm of sofa, more than across the sofa seat and back cushions, HGL developing
130	Flames begin spreading under and across the back of sofa
180	Flames rolling the ceiling above ignition area, HGL is approximately 0.9 m below the ceiling, smoke is spreading into open adjacent rooms
185	Flames spreading across ceiling toward open front door, transition to flashover started
195	Flames extending out the open front door
210	Living room fire fully developed
240	Burning visible near living room floor, smoke near floor level, flames exiting the front door become sooty and dark
290	Clean burning flames near the front doorway, smoke exiting front doorway reduced
330	Flames at front door become sooty again. Flames and smoke exiting the upper half of the front doorway
360	No flames visible exiting the front door, only smoke
380	Flames exiting upper portion of front door, flames exiting center gap of living room window shutters
460	Smoke reduced, clean burning flames fill the front doorway
540	Clean burning flames visible inside and exiting open front door
600	Flames can be seen on living room floor, and on furnishings
610	Fire suppression started with hose stream through open front doorway
640	Firefighters open living room shutters, fire suppression with hose stream continues through open living room window

Figure 4.18 displays the time history of the thermocouple temperatures in the living room. The growth of the hot gas layer, starting at the ceiling and descending to within a 0.3 m (1 ft) above the floor appears for the first 180 s. Seconds later, the temperatures of the thermocouples closest to the floor rapidly increased to more than 800 °C (1470 °F). Temperatures higher than 600 °C (1112 °F) from ceiling down to the floor would meet the defined conditions for flashover. Shortly after the transition to flashover, the temperatures in the living started to decrease, dropping to 500 °C (932 °F). At this point, oxygen had recovered because of the open front door, and temperatures rose again, remaining above 600 °C (1112 °F) until suppression.

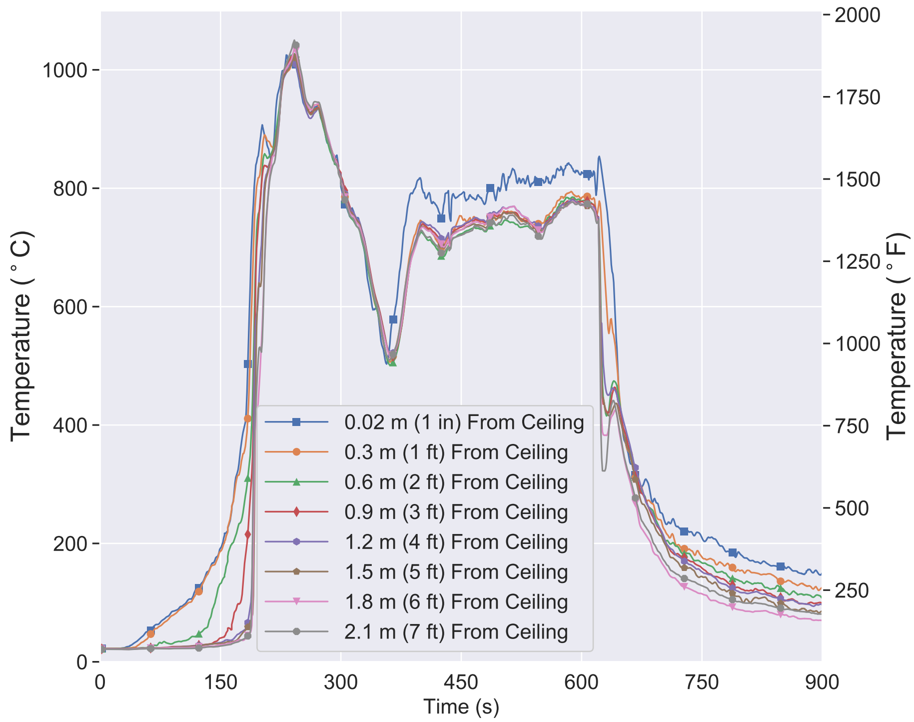


Figure 4.18: Experiment 4, front door open, living room temperature versus time.

Figure 4.19 shows the temperature profile at the front door. Initially the doorway was in pure exhaust flow before returning to being a bi-directional vent, with flames and smoke exiting the upper half of the doorway and fresh air being entrained through the lower half. This is noticeable in the distinct group of temperatures between the upper half and the lower half of the doorway.

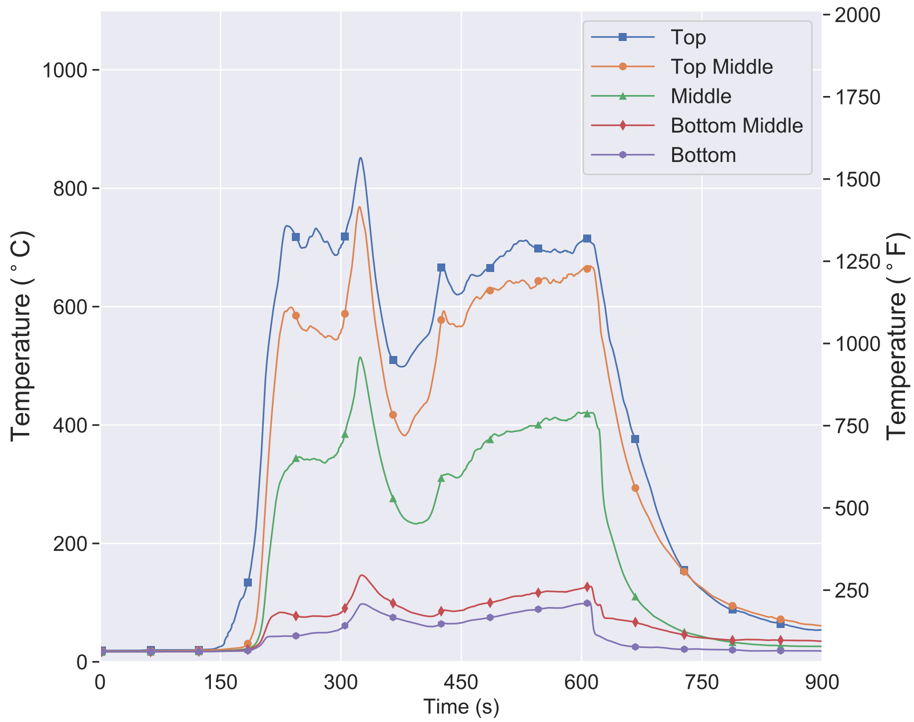
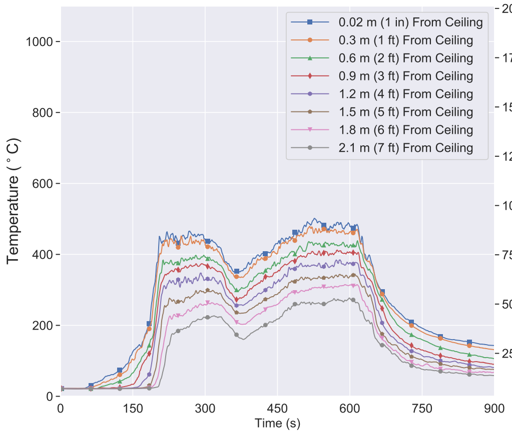
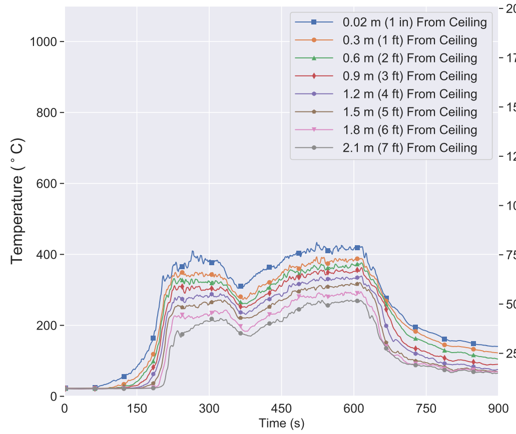


Figure 4.19: Experiment 4, front door open, front door temperature versus time.

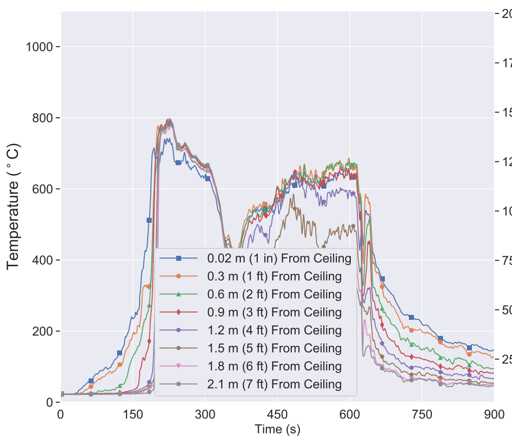
Figure 4.20 shows the temperature histories for the thermocouple array locations inside the single story structure. The dining room, kitchen, hallway, and bedroom 2 areas were open to the living room, and as a result the temperature trends follow those of the living room. The hallway thermocouple array was located the closest to the area of ignition while the bedroom 2, kitchen, and dining room thermocouples were further away. Being remote from the living room resulted in reduced peak temperatures. Only the hallway exceeded 600 °C (1112 °F) from ceiling down to the floor. The other rooms did not transition through flashover. The bedroom furniture in bedroom 2 did not ignite. The temperatures in the bedrooms with closed doors did not increase.



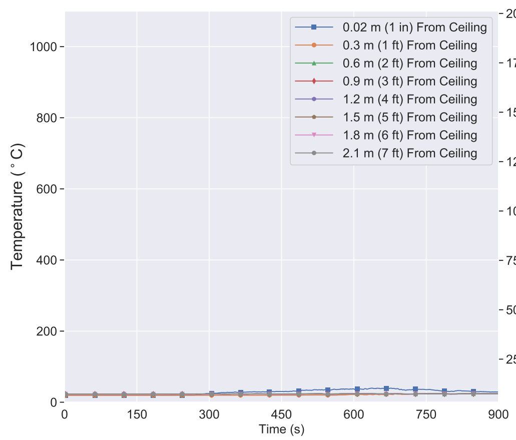
(a) Dining Room Temperature



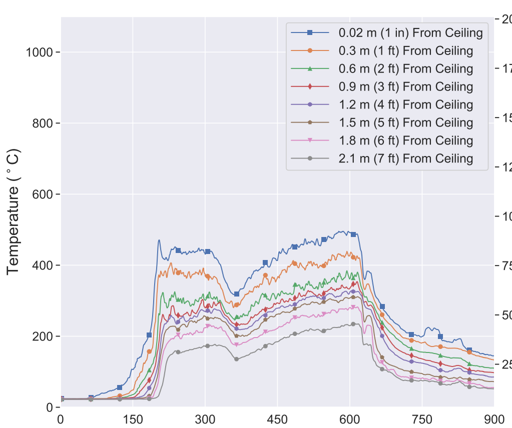
(b) Kitchen Temperature



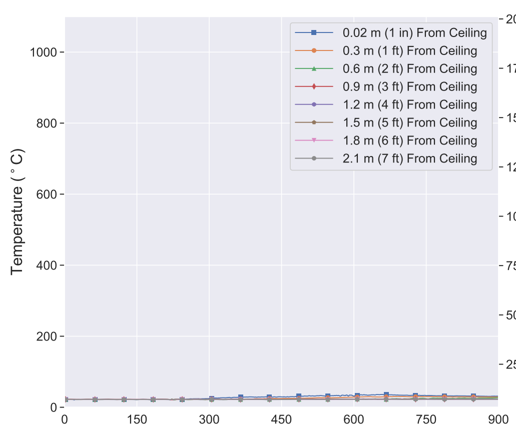
(c) Hallway Temperature



(d) Bedroom 1 Temperature



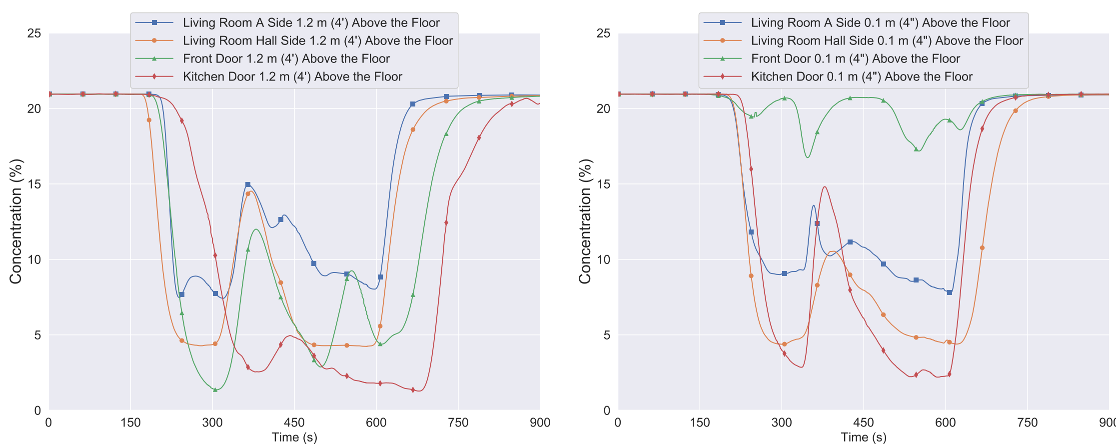
(e) Bedroom 2 Temperature



(f) Bedroom 3 Temperature

Figure 4.20: Experiment 4, front door open, time-temperature histories for all rooms.

Figure 4.21 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the point of ignition. Four of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.21a), and the other four were positioned under the upper sampling ports and 100 mm (4 in.) above the floor (see Figure 4.21b): two living room locations, one kitchen location, and a front door location. The four meters sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port. The oxygen meters measuring conditions to the right of the ignition sofa exhibited the earliest decrease at each level, which started at approximately 180 s and 200 s after ignition for the 1.2 m (4 ft) and the 100 mm (4 in.) sensors, respectively. Similar to Experiment 3 (see Figure 4.14) there was initial drop in oxygen at all sensor locations except for the front door 100 mm sensor. Oxygen within the structure began to rise at approximately 300 s, reaching a local maximum at 360 s. A second drop in oxygen concentration followed, with minimum values reached at approximately 500 s. The first minimum value in oxygen corresponds with the initial drop in temperature. A lack of oxygen in the structure limited combustion, and therefore temperatures decreased. As combustion products exited the structure through the top of open front door, oxygen returned through the bottom portion of the doorway as seen by the rise in oxygen reaching a local peak at approximately 360 s. At this point, oxygen returned to levels to support combustion. The result was a second spike in temperature and subsequent drop in oxygen.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.21: Experiment 4, front door open, oxygen concentration versus time.

During the initial fire growth and subsequent temperature rise in the living room (see Figure 4.18) the velocity profile at the front door shows that the door was completely an exhaust vent (see 200 s in Figure 4.22). The velocity profile at the interior hallway (Figure 4.23) at the same time shows the upper portion of the hallway flowing towards the bedrooms while the bottom probe indicates flow towards the fire. As the fire started to decay due to drop in oxygen concentration, the doorway velocity profile changed to a bi-drectional flow with the bottom two probes indicating air flowed into the structure.

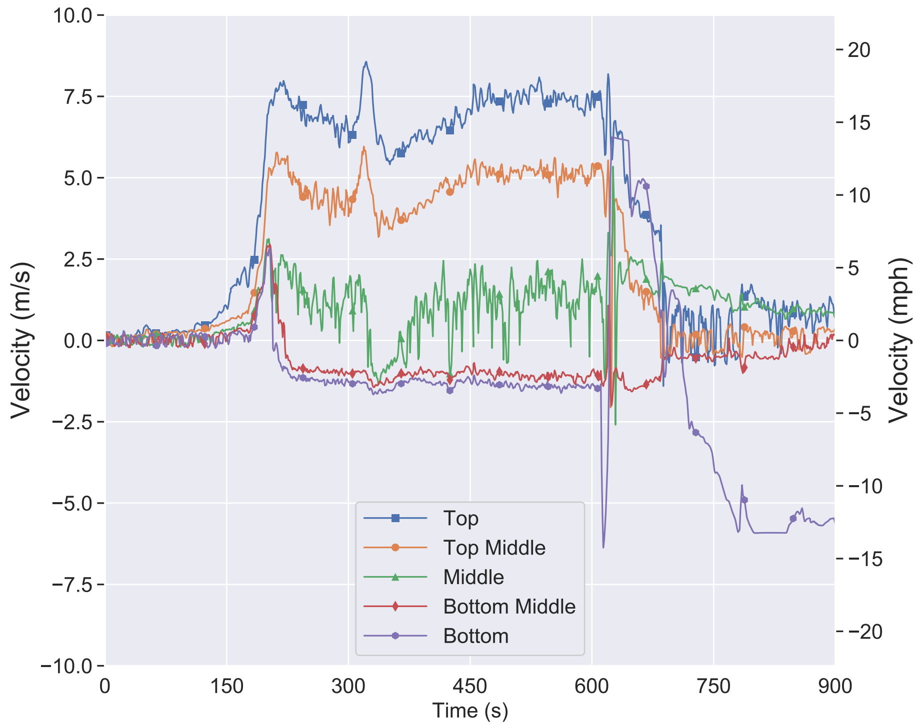


Figure 4.22: Experiment 4, front door open, front door velocity versus time.

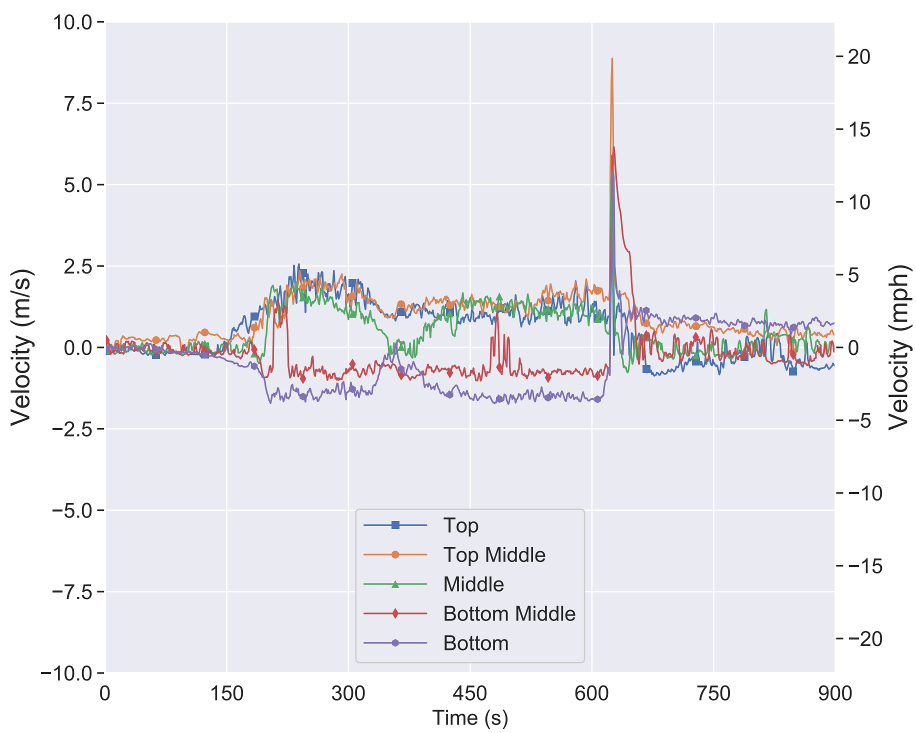
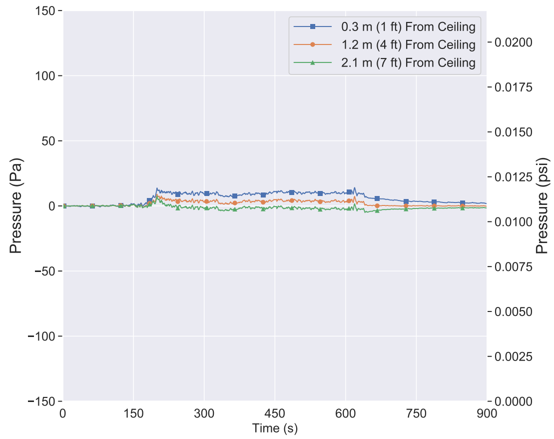
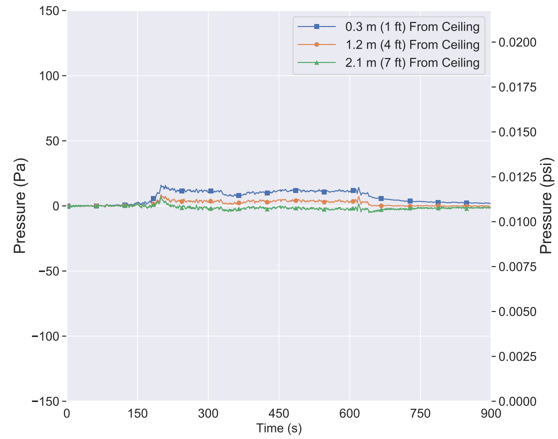


Figure 4.23: Experiment 4, front door open, hallway velocity versus time.

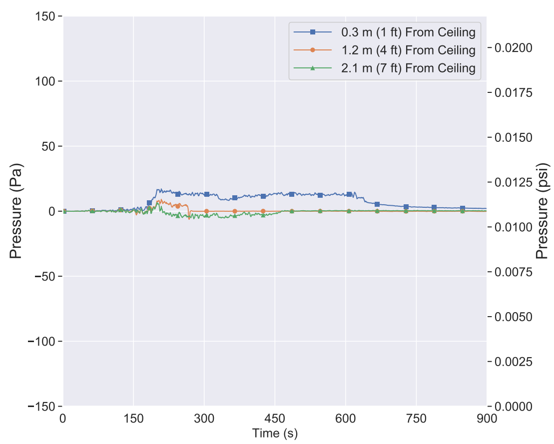
Figure 4.24 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. Unlike Experiments 1 and 2, pressures within the structure did not exceed 20 Pa because of the open front door. The rooms open to the living room had similar pressures. The two bedrooms with closed doors showed minimal pressure change.



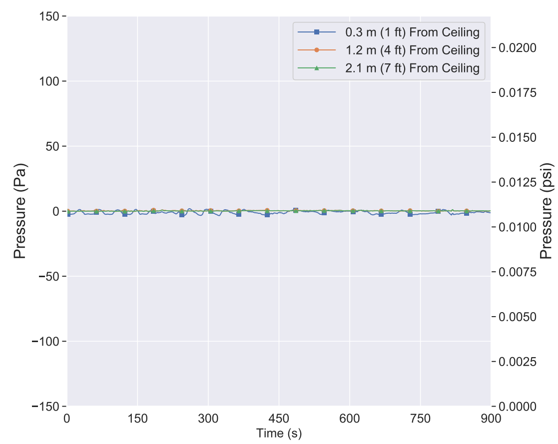
(a) Dining Room Pressure



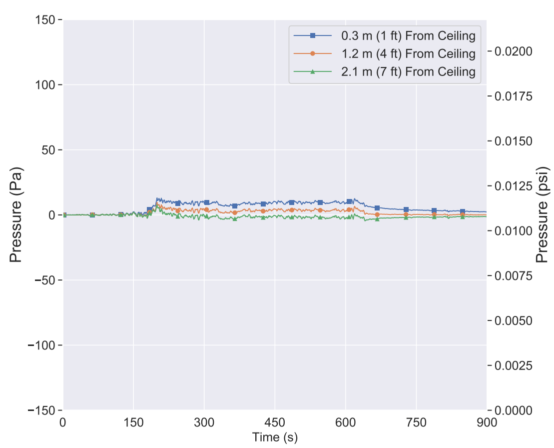
(b) Kitchen Pressure



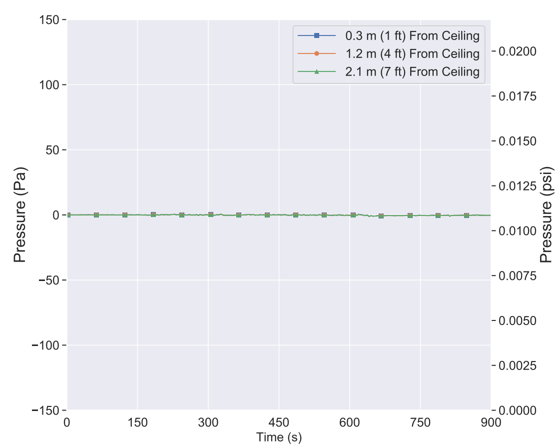
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.24: Experiment 4, front door open, pressures in all rooms.

Experiment 5

Similar to the previous living room experiments (Experiments 1–4), the sofa was ignited with a remotely operated electric match in the left corner of sofa. The difference is the front door, the door to bedroom 3, and the window in bedroom 3 were open for the duration of the experiment. The fire grew on the left side of the sofa, and a definitive thermal plume formed. Within a minute of ignition, flames reached the top of the sofa and began to spread across the top of the seat cushions, as had occurred in the first three experiments. Flames began to spread across the ceiling approximately three minutes after ignition. A minute later gray smoke flowed out of the front doorway and bedroom 3 window opening. Approximately five minutes post ignition, flames were visible out of the top third of the front door while black smoke flowed from the top half of the open window in bedroom 3. At this point, the living room had transitioned to flashover.

Similar to Experiment 4, flames initially exiting the front door after flashover were shrouded in unburned soot. Approximately 90 s post-flashover, the soot was gone and clean burning flames filled the upper half of the doorway. At eight minutes after ignition, the smoke exiting the bedroom window had dissipated and flames were observed on the bedding. Thirty seconds later, flames exited the window. Flaming combustion persisted at both the doorway and window until suppression at 10 min after ignition. Table 4.6 provides a description of events.

Table 4.6: Timeline for Experiment 5, Living Room Fire with Front Door Open and Bedroom 3 Window

Time (s)	Event
0	Ignition on the left side of the sofa
25	Flames extended past the top of the back of the sofa, gypsum board exposed to flame
60	Flames approximately 1.2 m above sofa seat, ceiling jet moving smoke across the living room ceiling, light gray smoke exiting front doorway
120	Horizontal flame spread along arm of sofa, more than across the sofa seat and back cushions, HGL developing
180	Flames rolling the ceiling above ignition area, HGL approximately 0.9 m below the ceiling, smoke is spreading into open adjacent rooms
240	Gray smoke flowing out of the front doorway and bedroom 3 window opening
295	Flames visible out of the top third of the front door while black smoke flowed from the top half of the open window in bedroom 3
300	Living room transitioned to flashover, flames exiting front door shrouded in soot
390	Flame out top half of front door, soot free
480	Smoke exiting the bedroom 3 window had dissipated and flames were observed on the bedding
510	Flames exiting open bedroom 3 window
600	Fire suppression started with hose stream through open front doorway
620	Fire suppression with hose stream continues through open bedroom room window

Figure 4.25 displays the time history of the thermocouple temperatures in the living room. The growth of the hot gas layer, starting at the ceiling and descending to within a 0.3 m (1 ft) above the floor appears for the first 150 s–175 s. Seconds later, the temperatures of the thermocouples closest to the floor rapidly increased to more than 800 °C (1470 °F). With the additional ventilation of the open front door and open bedroom 3 window, the fire remained in a fully developed state with temperatures above 600 °C (1112 °F), until suppression 600 s post ignition..

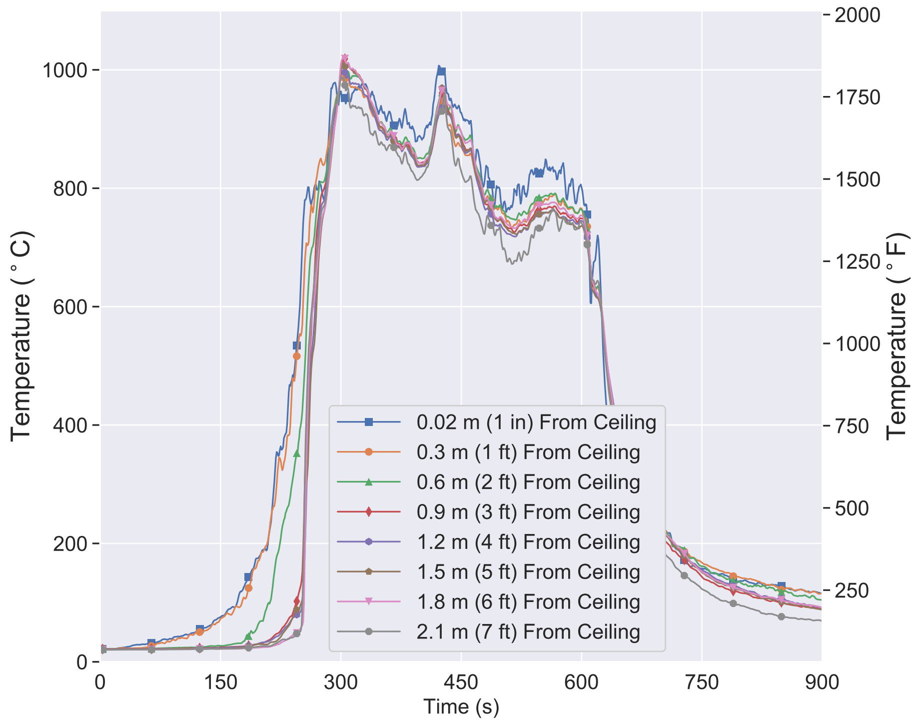
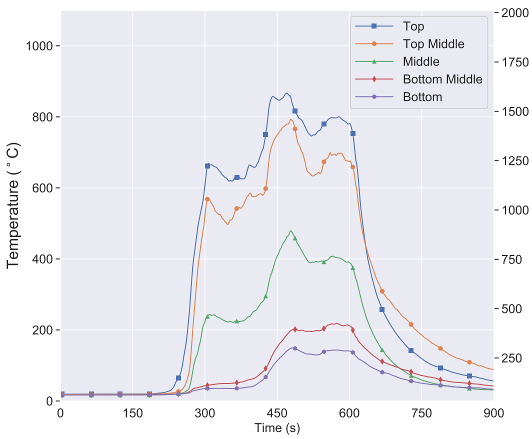
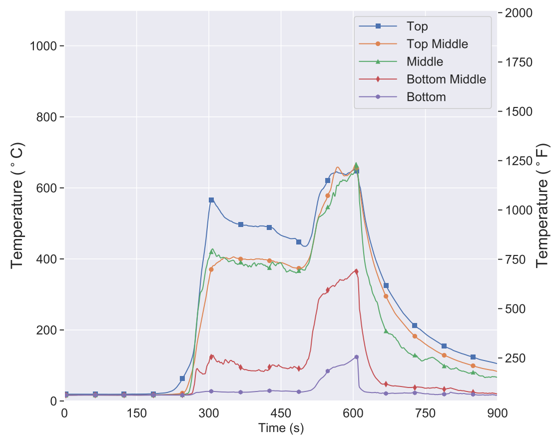


Figure 4.25: Experiment 5, front door and bedroom 3 window open, living room temperature versus time.

Figure 4.26a shows the temperature profile at the front door while Figure 4.26b shows the temperature profile at the bedroom 3 window. At the front door, the temperature profile is split about and below the middle probe regarding flow at the doorway. At 295 s post ignition, the top two probes in Figure 4.26a correspond to when flames were first reported at the front door. The temperature gradient at the bedroom 3 window is similar, and Figure 4.26b shows when there was flaming combustion at the window via top three thermocouples.



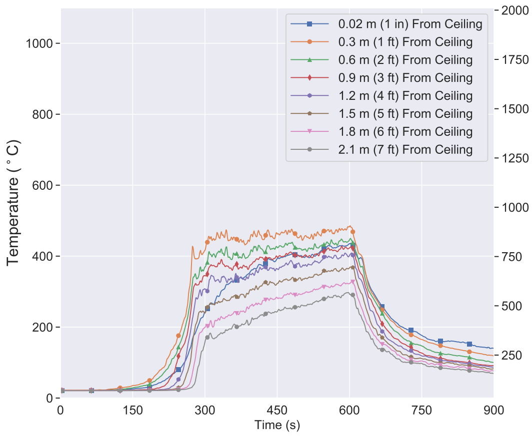
(a) Front Door Temperature



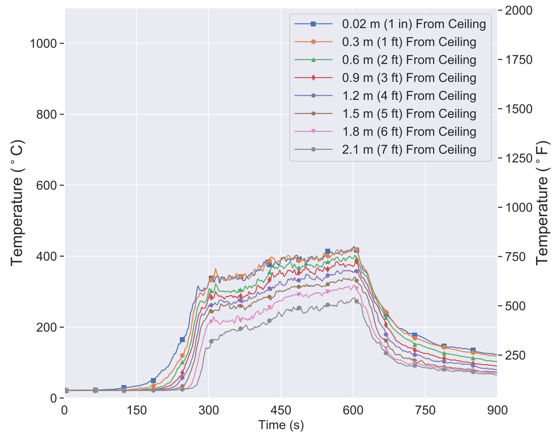
(b) Bedroom 3 Window Temperature

Figure 4.26: Experiment 5, front door and bedroom 3 window open, front door temperature and bedroom 3 window versus time.

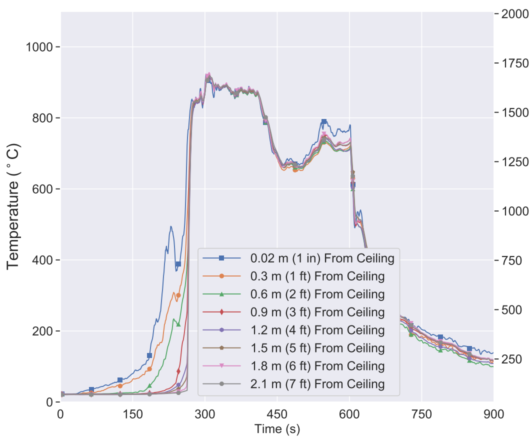
Figure 4.27 shows the temperature histories for the thermocouple array locations inside the single story structure. The dining room, kitchen, hallway, bedroom 2, and bedroom 3 areas were open to the living room, and as a result the temperature trends follow those of the living room. The hallway thermocouple array was located the closest to the area of ignition, while the bedroom 2, kitchen, and dining room thermocouples were further away. The hallway thermocouple array was also in a flow path because of the open bedroom window. Being remote from the living room resulted in reduced peak temperatures. The hallway exceeded 600 °C (1112 °F) from ceiling down to the floor, reflecting the living room. The open window in bedroom 3 eventually led to floor to ceiling temperatures to be 600 °C (1112 °F) as the bedding caught fire and flames exited the window. The other rooms did not transition through flashover. The bedroom furniture in bedroom 2 did not ignite. The temperatures in the bedrooms with closed doors did not increase.



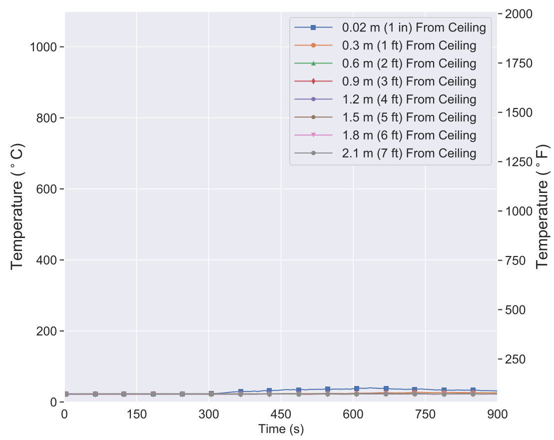
(a) Dining Room Temperature



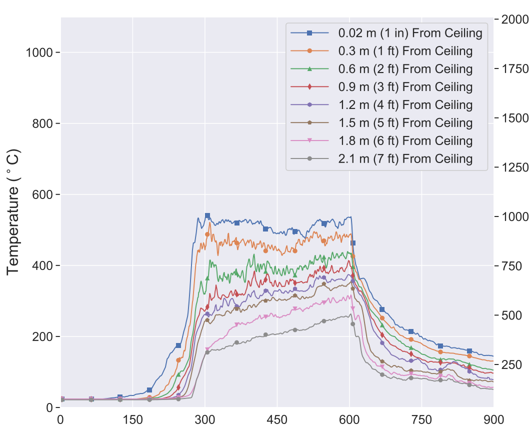
(b) Kitchen Temperature



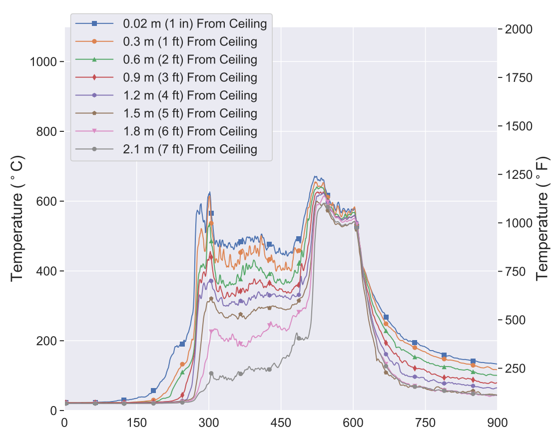
(c) Hallway Temperature



(d) Bedroom 1 Temperature



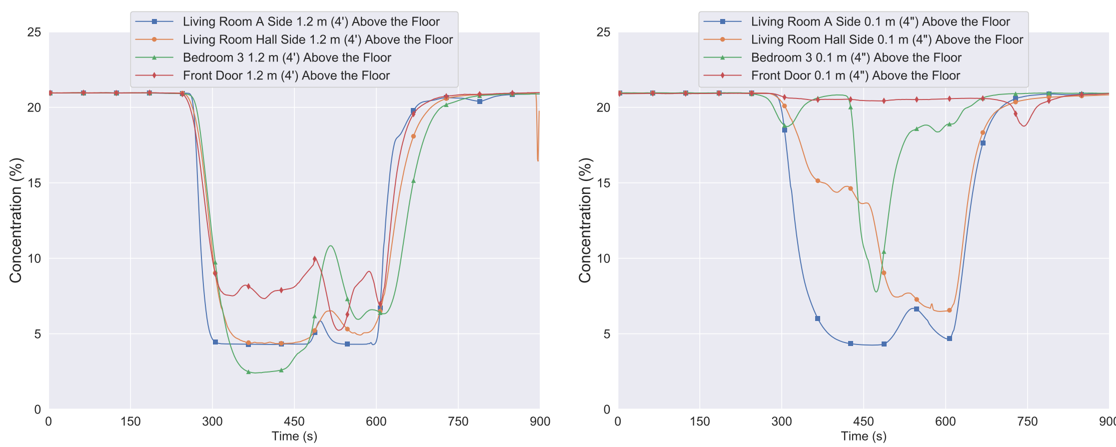
(e) Bedroom 2 Temperature



(f) Bedroom 3 Temperature

Figure 4.27: Experiment 5, front door and bedroom 3 window open, temperature time histories for all rooms.

Figure 4.28 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the point of ignition. Four of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.28a), and the other four were positioned under the upper sampling ports and 100 mm (4 in.)above the floor (see Figure 4.28b): two living room locations, a bedroom 3 location, and a front door location. The four meters sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port. The oxygen meters measuring conditions to the right of the ignition sofa exhibited the earliest decrease at each level, which started at approximately 260 s–270 s after ignition for the 1.2 m (4 ft) and the 100 mm (4 in.). Similar to Experiments 3 and 4, (see Figures 4.14 and 4.21) there was initial drop in oxygen at all sensor locations except for the front door 100 mm sensor. The oxygen at 100 mm in bedroom 3 had initial drop resulting from the surge of combustion products into the room (see initial spike in temperature in Figure 4.27f), a recovery, followed by a steep decay as a result of the contents igniting. The remainder of the oxygen sensors dropped and remained between 5%–10% until the fire was suppressed.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.28: Experiment 5, front door and bedroom 3 window open, oxygen concentration versus time at 1.2 m and 0.1 m above floor.

During the initial fire growth and subsequent temperature rise in the living room (see Figure 4.25), the velocity profile at the front door shows that the door was completely an exhaust vent (see 275 s in Figure 4.29). The velocity profile at the interior hallway (see Figure 4.30) at the same time shows the upper portion of the hallway flowing towards the bedrooms while the bottom probe indicates flow towards the fire. As the fire started to decay due to drop in oxygen concentration, the doorway velocity profile changed to a bi-drectional flow with the bottom two probes indicating air flowed into the structure. The exhaust flow at the top of the front doorway was steady between 4.5 m/s (10 mph)–6 m/s (13 mph) for the top two probes, respectively.

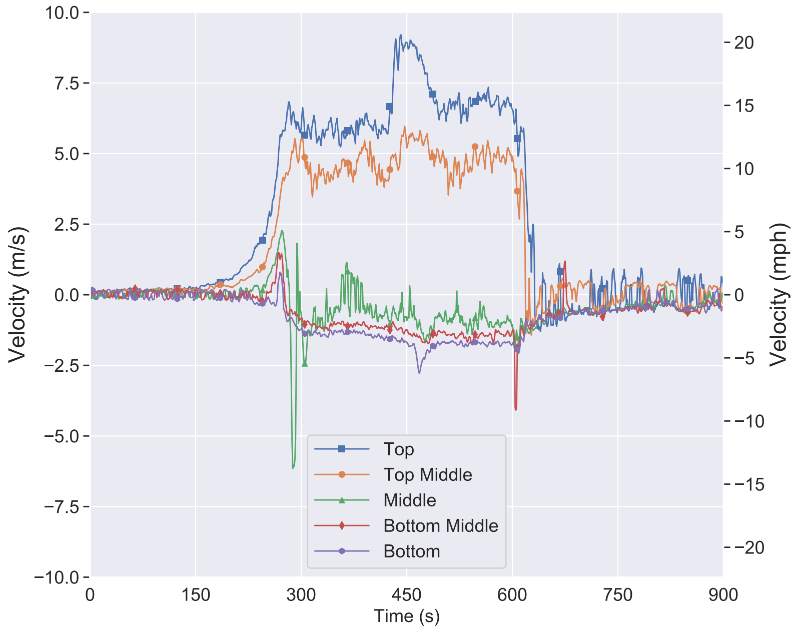


Figure 4.29: Experiment 5, front door and bedroom 3 window open, front door velocity versus time.

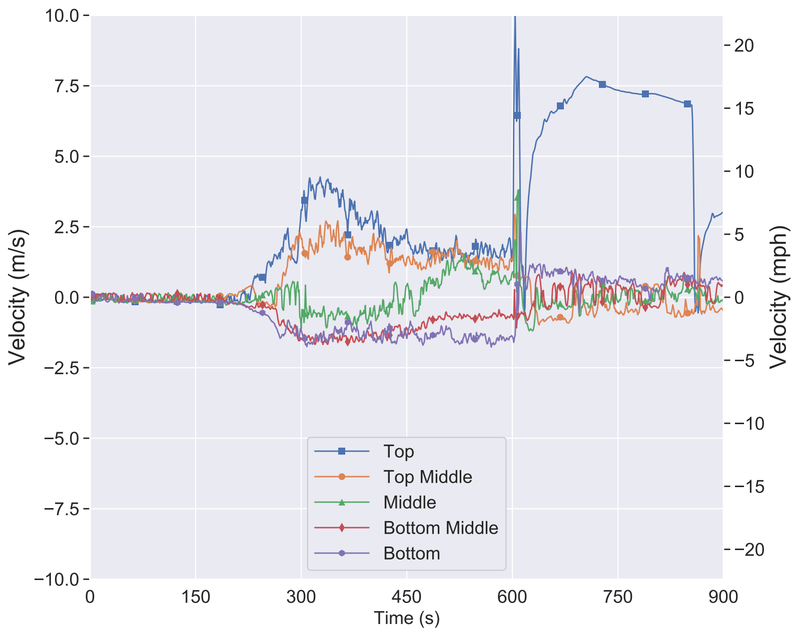


Figure 4.30: Experiment 5, front door and bedroom 3 window open, hallway velocity versus time.

For the bedroom 3 window, after an initial surge (see Figure 4.31) where all probes indicated exhaust flow, the top three probes showed consistent outflow flow for the remainder of the experiment. The bottom two probes measured inflow at the window at approximately 0.5 m/s (1.1 mph) until about 500 s after ignition when the bed started flaming. The top three probes ranged between

3 m/s (6.7 mph) and 7.5 m/s (16.5 mph).

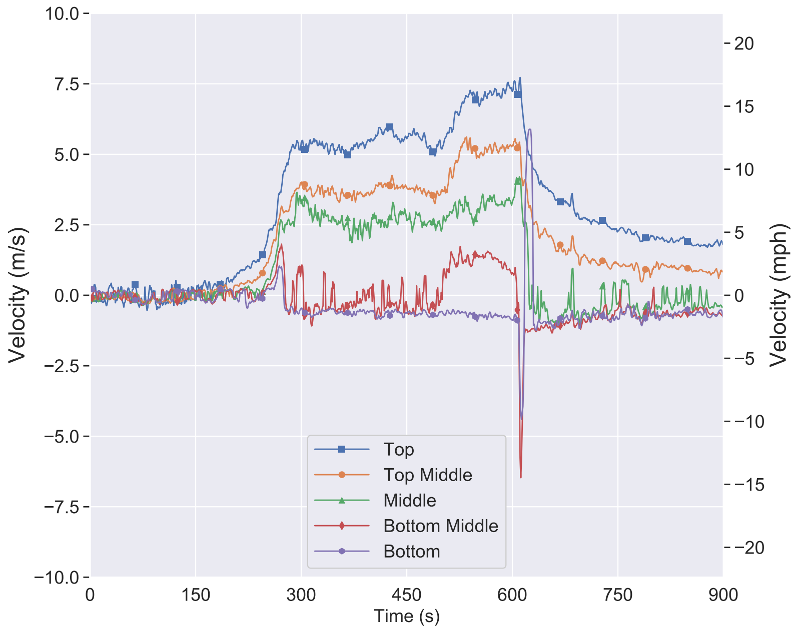
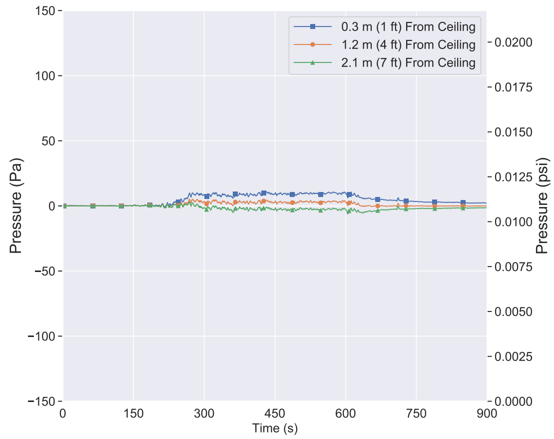
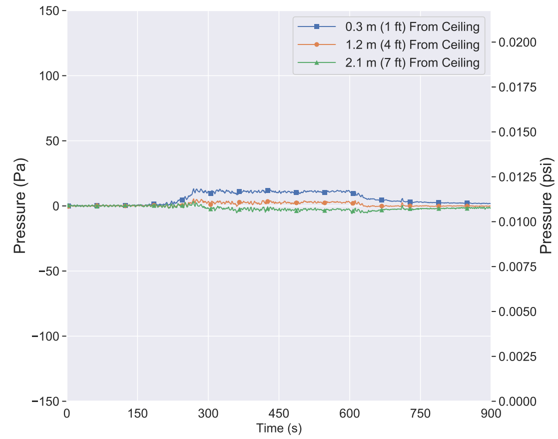


Figure 4.31: Experiment 5, front door and bedroom 3 window open, bedroom 3 window velocity versus time.

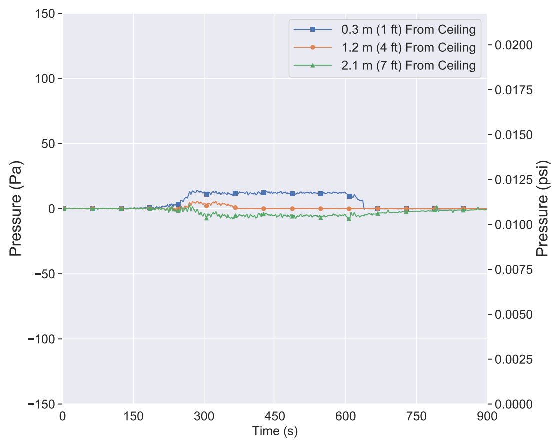
Figure 4.32 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. Unlike Experiments 1 and 2, pressures within the structure did not exceed 20 Pa because of the open front door. The rooms open to the living room had similar pressures. The two bedrooms with closed doors showed minimal pressure change.



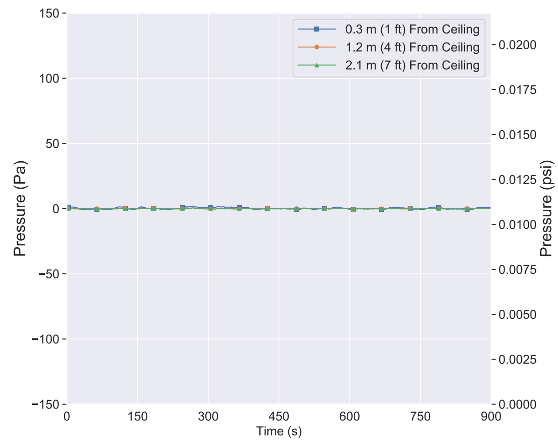
(a) Dining Room Pressure



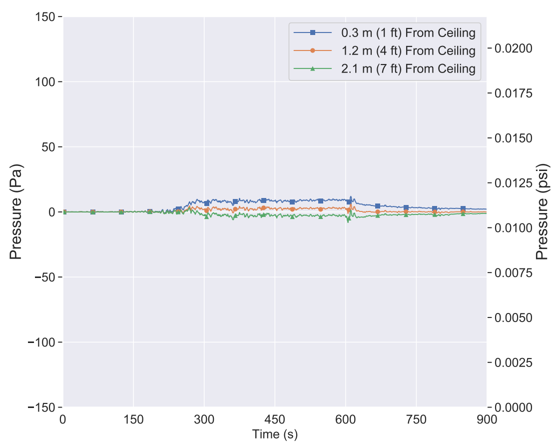
(b) Kitchen Pressure



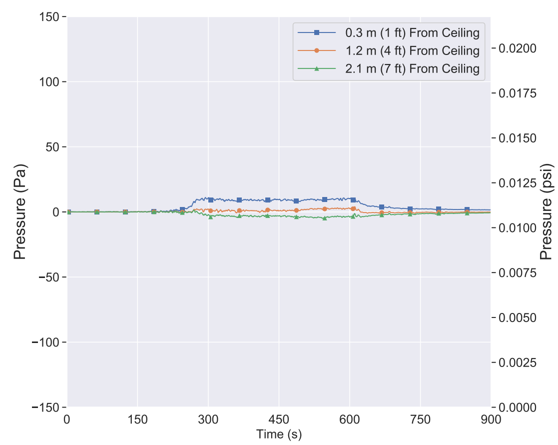
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.32: Experiment 5, front door and bedroom 3 window open, pressures in all rooms

4.2 Kitchen Fires

The kitchen fire experiments added a number of elements to the test series that were different from the living room and bedroom fire experiments. The ignition was located approximately 0.9 m (3 ft) above the floor, fuel package consisted of many solid fuels, including medium density fiberboard cabinets, plastics and plastic laminates, and vinyl flooring. The ignition package included an electrically modified coffee maker (all thermal fuse protection was removed). The 12-cup, plastic shrouded coffee maker had 50 0.23 L (8 fl. oz) capacity expanded polystyrene hot serve cups weighing 0.1 kg (0.2 lbs) arranged in three stacks on the right of the coffee maker, and a 0.45 kg (16 oz) bag of potato chips on the right side.

The fuels in the cabinet above the ignition package included: 1 kg (2.2 lb) of 0.53 L (18 oz) capacity polyethylene terephthalate (PET) drinking cups, 4.5 kg (9.9 lb) of 0.47 L (16 fl. oz) capacity unexpanded polystyrene cups, and a 0.45 kg (16 oz) bag of potato chips.

Two experiments were conducted with all of the exterior vents closed. On the interior, the doors to bedrooms 1 and 3 were also closed for each experiment. Two experiments were conducted with a single exterior vent, the front door, open at the start of the experiment and through the fire growth period in the kitchen. The doors to bedrooms 1 and 3 were also closed for both of these experiments.

To start the fire, the coffee maker was plugged in an energized circuit. As the thermal element continued to heat without any thermostatic control or protection, the plastic in the area of the heating element began to pyrolyze, and then the gaseous vapors ignited. In three of the experiments, this process took less than 10 minutes. Once the flaming occurred, this time was considered time zero or the start of the fire experiment. One of the experiments required the used of a manually applied open flame to ignite the gas created by the heating element.

4.2.1 All Exterior Vents Closed

Experiment 6

The experiment began with the observation of flames near the base of the coffee maker. Within a minute, the flames had increased in size and were impinging on the bottom of the wall cabinet above the coffee maker. As the flames grew in size, the expanded foam coffee cups were ignited. Two minutes after the start of the experiment, the stacks of burning cups began to fall and spread the area of fire.

Approximately 3 min and 30 s after the flaming ignition of the coffee maker, the flames had spread to the point where the flames extended up the front and right side of the wall cabinet, involving the cabinet door and wall material, while heating the fuels inside the cabinet. At the same time, a light gray colored smoke layer approximately 0.91 m (3 ft) below the ceiling had developed in the kitchen and was spreading throughout the open areas of the structure.

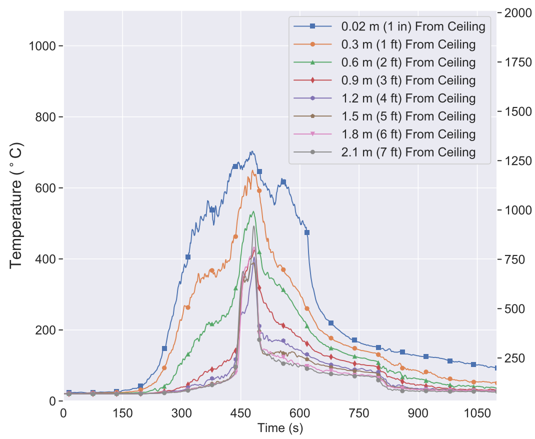
Five minutes after the first visible flames, the fire continued to grow in energy release and size. The flames were impacting the ceiling and the color of the smoke changed from gray to black. The hot gas layer descended to within a 0.3 m (1 ft) of the kitchen floor.

The fire appeared to reach its peak about 8 min after visible flaming, and the size and the heat generated by the fire began to decrease in size. Within 30 s of the start of the decrease, no visible flames could be seen. A few seconds later, the shelves of the wall cabinet could be observed collapsing. Firefighters opened the kitchen doorway more than 13 minutes after ignition. No rekindle occurred, and hot spots were extinguished with a hand-held, pressurized-water extinguisher. Table 4.7 provides a timeline of the fire development.

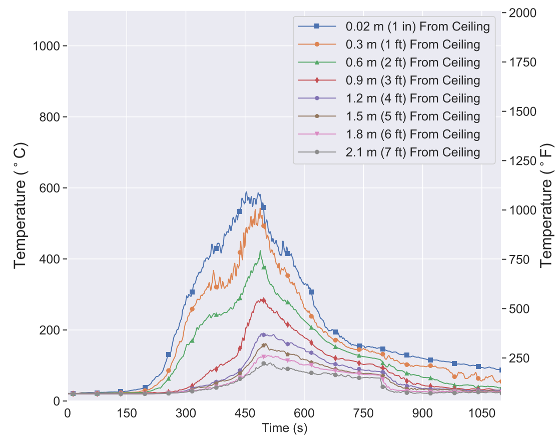
Table 4.7: Timeline for Experiment 6, Kitchen Fire with Closed Front Door

Time (s)	Event
0	Ignition
60	Fire increased in size and impinged on the bottom of the wall cabinet above the coffee maker
120	Stacks of burning cups fell and spread the area of fire
210	Flames had spread to the point where they extended up the wall cabinet, and a light gray colored smoke layer approximately 0.91 m (3 ft) below the ceiling developed in the kitchen
300	Flames reached the ceiling, the color of the smoke changed from gray to black, HGL descended to within a 0.3 m (1 ft) of the kitchen floor
480	Kitchen fire reached its peak and started to decay
510	Flames no longer visible
515	Shelves of the wall cabinet began collapsing
780	Firefighters open kitchen door and extinguished hot spots with pressurized water can.

Figure 4.33 shows the temperature profiles for both the kitchen temperature and the adjacent kitchen area temperature. In both arrays, the temperature rose as the fire spread in the kitchen with peak temperatures just over 600 °C (1112 °F) at the 0.02 m and 0.3 m distance below the ceiling in the kitchen. The temperatures peaked approximately 480 s after ignition without either space transitioning to flashover due to a lack of oxygen. The temperatures then decayed as the fire self extinguished.



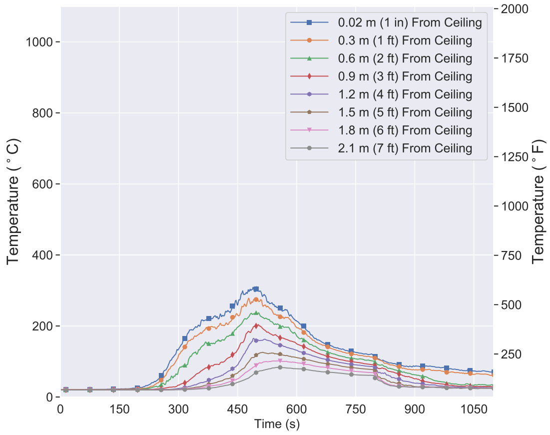
(a) Kitchen Temperature



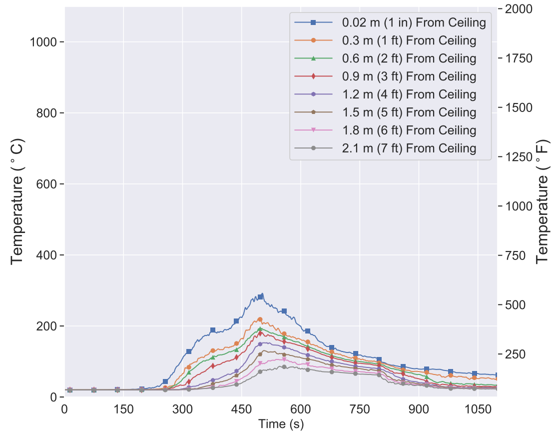
(b) Breakfast Area Temperature

Figure 4.33: Experiment 6, no exterior ventilation openings, kitchen (top) and breakfast area (bottom) temperatures versus time.

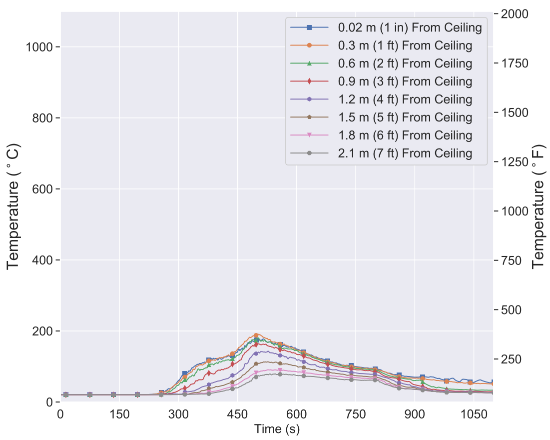
Figure 4.34 shows the temperature histories for the thermocouple array locations inside the single story structure. The dining room, living room, hallway, and bedroom 2 areas were open to the kitchen, and as a result the temperature trends follow those of the kitchen. The breakfast area (see Figure 4.33 bottom) and dining room thermocouple array (see Figure 4.34a) were the two closest arrays to the area of ignition while the bedroom 2, living room, and hallway thermocouples were further away. Being remote from the kitchen resulted in reduced peak temperatures. The breakfast area temperature, which was closest to the kitchen ignition, reached approximately 300 °C (572 °F) at ceiling with cooler temperatures closer to the floor. The temperatures in the bedrooms with closed doors did not increase.



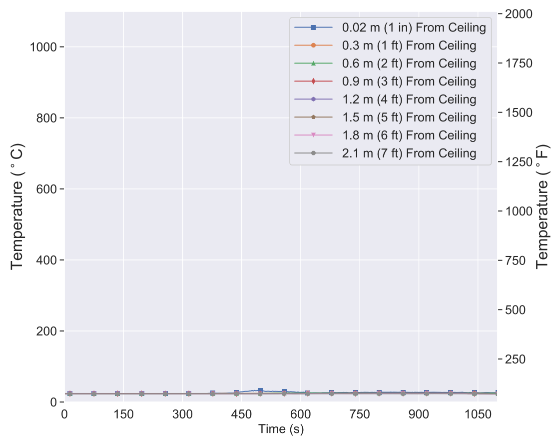
(a) Dining Room Temperature



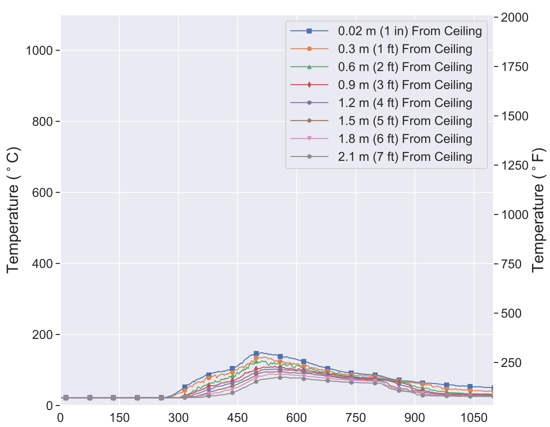
(b) Living Room Temperature



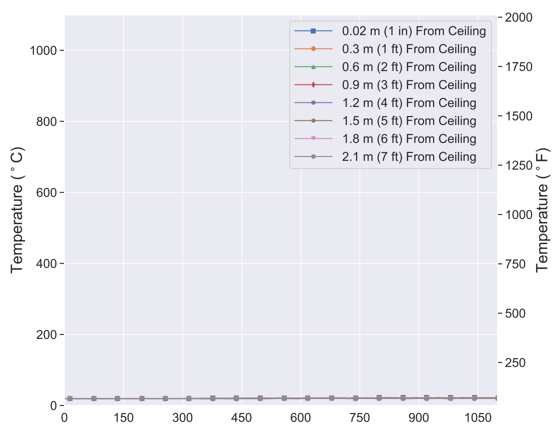
(c) Hallway Temperature



(d) Bedroom 1 Temperature



(e) Bedroom 2 Temperature

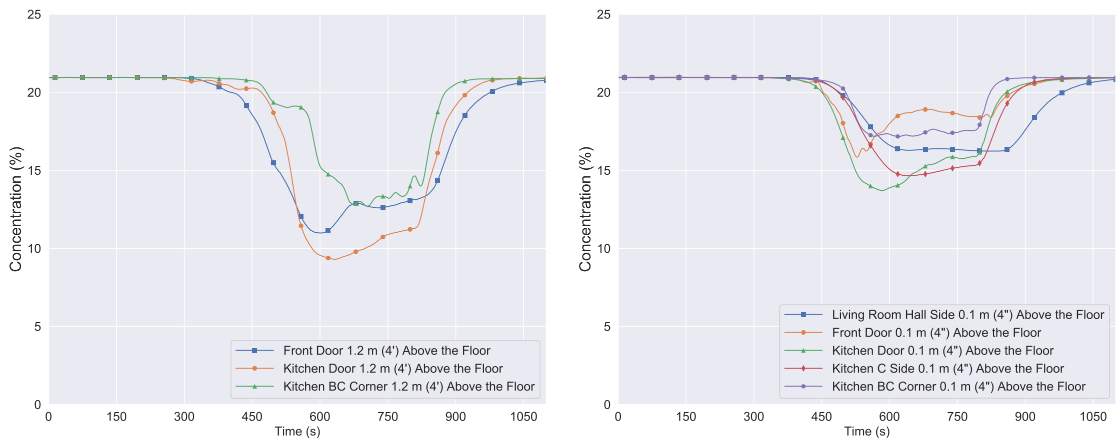


(f) Bedroom 3 Temperature

Figure 4.34: Experiment 6, no exterior ventilation openings, temperature time histories for all rooms.

Figure 4.35 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the ignition within the kitchen as well to include locations in the living room and front door. Three of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.35a), and the other five were positioned 100 mm (4 in.) above the floor (see Figure 4.35b). The four meter sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port.

The oxygen meters measuring conditions at the 1.2 m (4 ft) level started to decrease at 300 s with the most distinct drop in oxygen concentration in the kitchen and at the front door occurring at approximately 450 s. The oxygen meters that measured gases sampled at 1.2 m (4 ft) above the floor had minimum oxygen concentrations between 9.3%–12.7%. The oxygen meters that measured gases sampled at 100 mm (4 in.)had minimum oxygen concentrations of 13.7% or greater. The elevated fuel (0.9 m (3 ft) height) of the kitchen fire and low oxygen concentrations at the 1.2 m (4 ft) level combined with the closed front door closed resulted in a fire that self-extinguished.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.35: Experiment 6, no exterior ventilation openings, oxygen concentration versus time at 1.2 m and 0.1 m above the floor.

Figure 4.36 shows the velocities from the measurement array in the hallway. The velocities provide some insight into the gas flow circulation into and out of bedroom 2. The gases flowing into the bedroom are shown with a positive velocity, and gases out of the bedroom are shown with a negative velocity. When the fire was near its peak burning rate, more than the top half of the hallway had gases exhausting into the bedroom room at velocities of about 1 m/s (2.2 mph). At the same time, denser, cooler, gases were flowing into the bottom of the living room at about 1 m/s (2.2 mph). As the fire decreased in size, the exhaust gases began to slow. The middle of the hallway had a flow of roughly 0.2 m/s (0.5 mph). Note: The top velocity probe failed during this experiment.

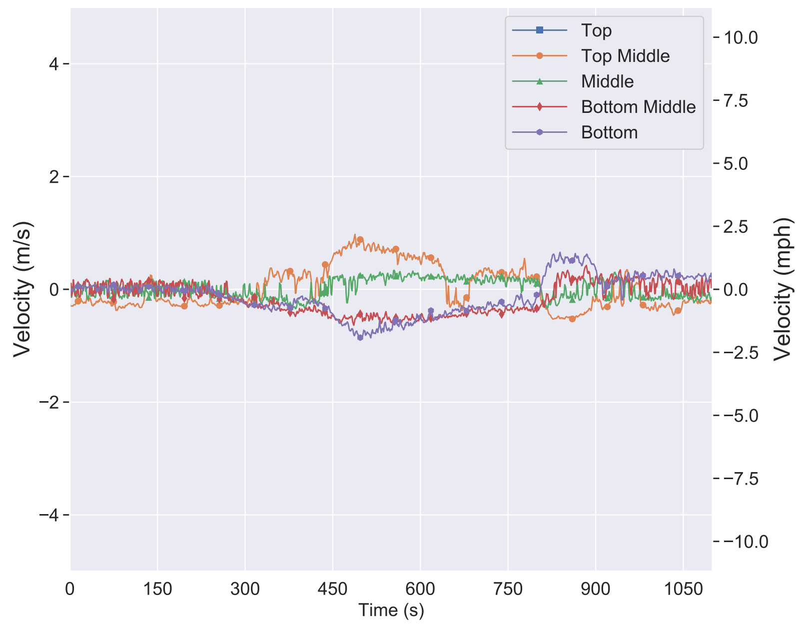
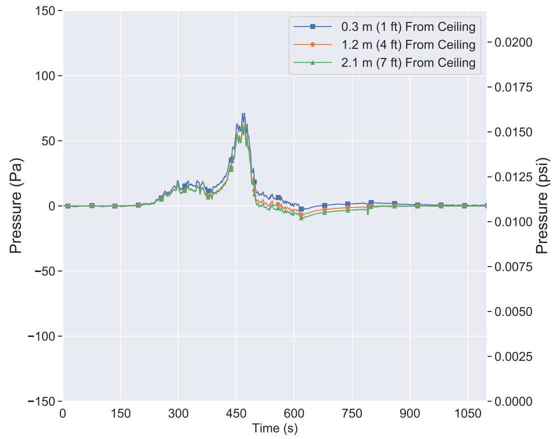
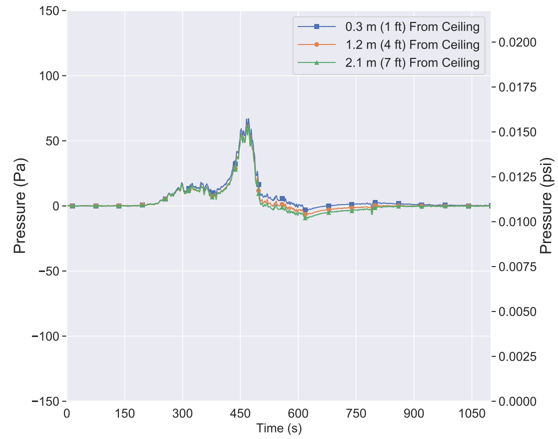


Figure 4.36: Experiment 6, no exterior ventilation openings, hallway velocity versus time. Positive pressure flowing from kitchen/living room to bedroom 2.

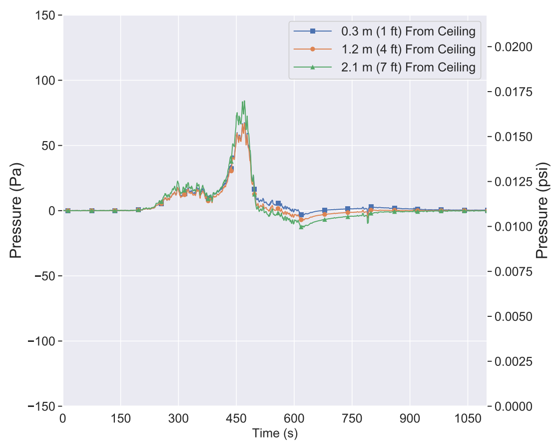
Figure 4.37 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. For the kitchen and rooms open to the kitchen (i.e., dining room, living room, and bedroom 2), pressures peaked between 60–70 Pa due to the lack of exterior ventilation. The pressures peaked at similar temperatures within the structure. The two bedrooms with closed doors showed minimal pressure change, with bedroom 1 showing an increase of less than 10 Pa and bedroom 3 showing no noticeable rise.



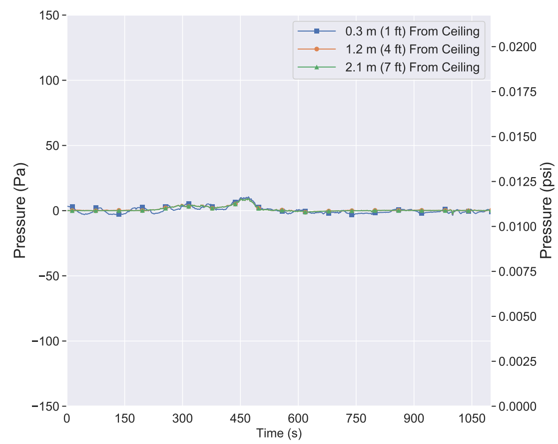
(a) Dining Room Pressure



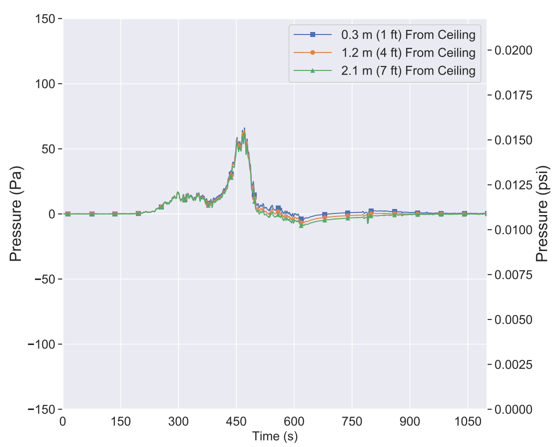
(b) Kitchen Pressure



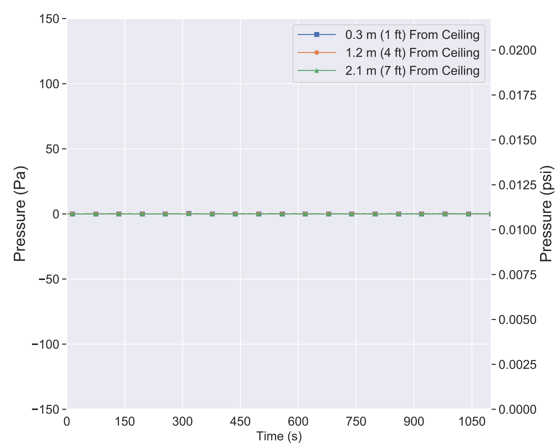
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.37: Experiment 6, no exterior ventilation openings, pressures in all rooms

Experiment 8

Similar to the previous experiment (Experiment 6), the observation of flames near the base of the coffee maker (ignition) served as the start of this experiment. The progression of the fire was also similar: Within a minute of the appearance of the fire, the flames had increased in size and impinged on the bottom of the wall cabinet above the coffee maker. Flames quickly spread to the bag of potato chips. As a result, the flames had extended up the front and the right side of the wall cabinet within 90 s of ignition.

Approximately 2 min and 30 s after the flaming ignition of the coffee maker, flames impinged on the ceiling. A light gray colored smoke layer approximately 0.91 m (3 ft) below the ceiling had developed in the kitchen and had spread throughout the open areas of the structure. During the next 2 min and 30 s the fire continued to burn in the area of origin and the wall cabinet above it. The color of the smoke changed from light gray to black and the hot gas layer was now approximately 1.2 m (4 ft) thick.

The fire appeared to reach its peak within 7 min after ignition. At this point, the lower edge of the hot gas layer was within 0.3 m (1 ft) of the floor. As the fire started to diminish in size, the cabinet doors began to come apart. Three min and 45 s after the peak the fire appeared to self-extinguish. Seconds later the shelves of the wall cabinet began collapsing, and there appeared to be additional burning for an additional minute before cessation of combustion. Firefighters opened the kitchen doorway approximately 13 min after ignition. No rekindle occurred and hot spots were extinguished with a hand-held, pressurized-water, extinguisher. The timeline for this experiment appears in Table 4.8.

Table 4.8: Timeline for Experiment 8, Kitchen Fire with Closed Front Door

Time (s)	Event
0	Ignition
60	Fire increased in size and impinged on the bottom of the wall cabinet above the coffee maker
90	Flames extended up the front and the right side of the wall cabinet
210	Flames impinged on ceiling, and alight gray colored smoke layer approximately 0.91 m (3 ft) below the ceiling developed in the kitchen
420	Kitchen fire reached its peak, HGL was within 0.3 m (1 ft) of the floor
645	Flames no longer visible, fire appeared to self extinguish
650	Shelves of the wall cabinet began collapsing
780	Firefighters opened kitchen door and extinguished hot spots with pressurized water can

Figure 4.38 shows the breakfast area temperature. The kitchen thermocouple array failed during the experiment, so while examining the breakfast area temperature it is important to recall that the thermal conditions are less severe than the kitchen as shown in Figure 4.33. Similar to Experiment 6, the breakfast area temperature rose with the kitchen fire growth, peaked prior to a transition to flashover, and extinguished from a lack of oxygen.

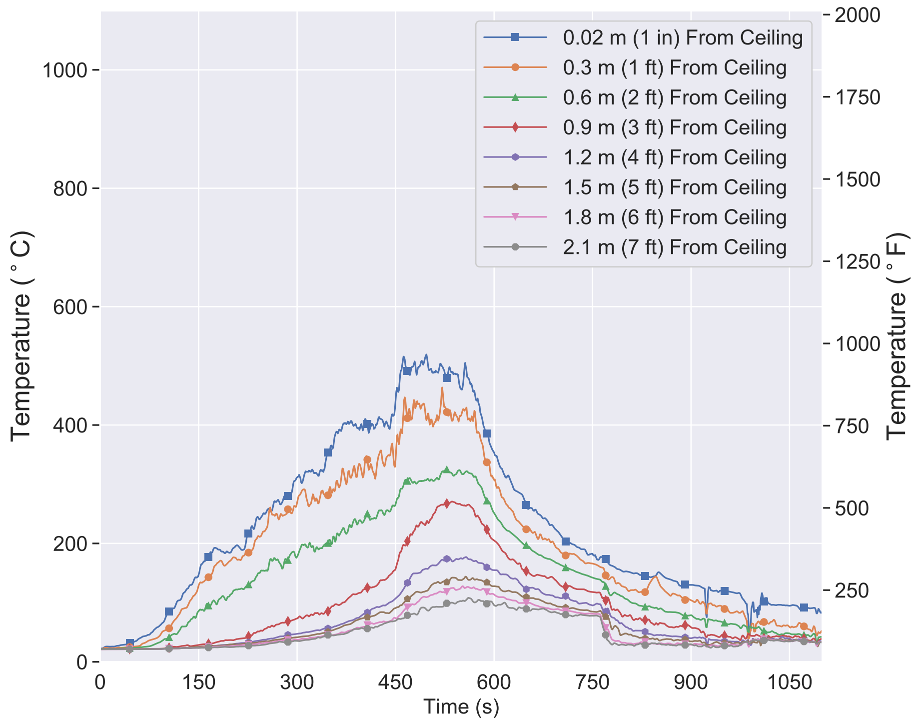
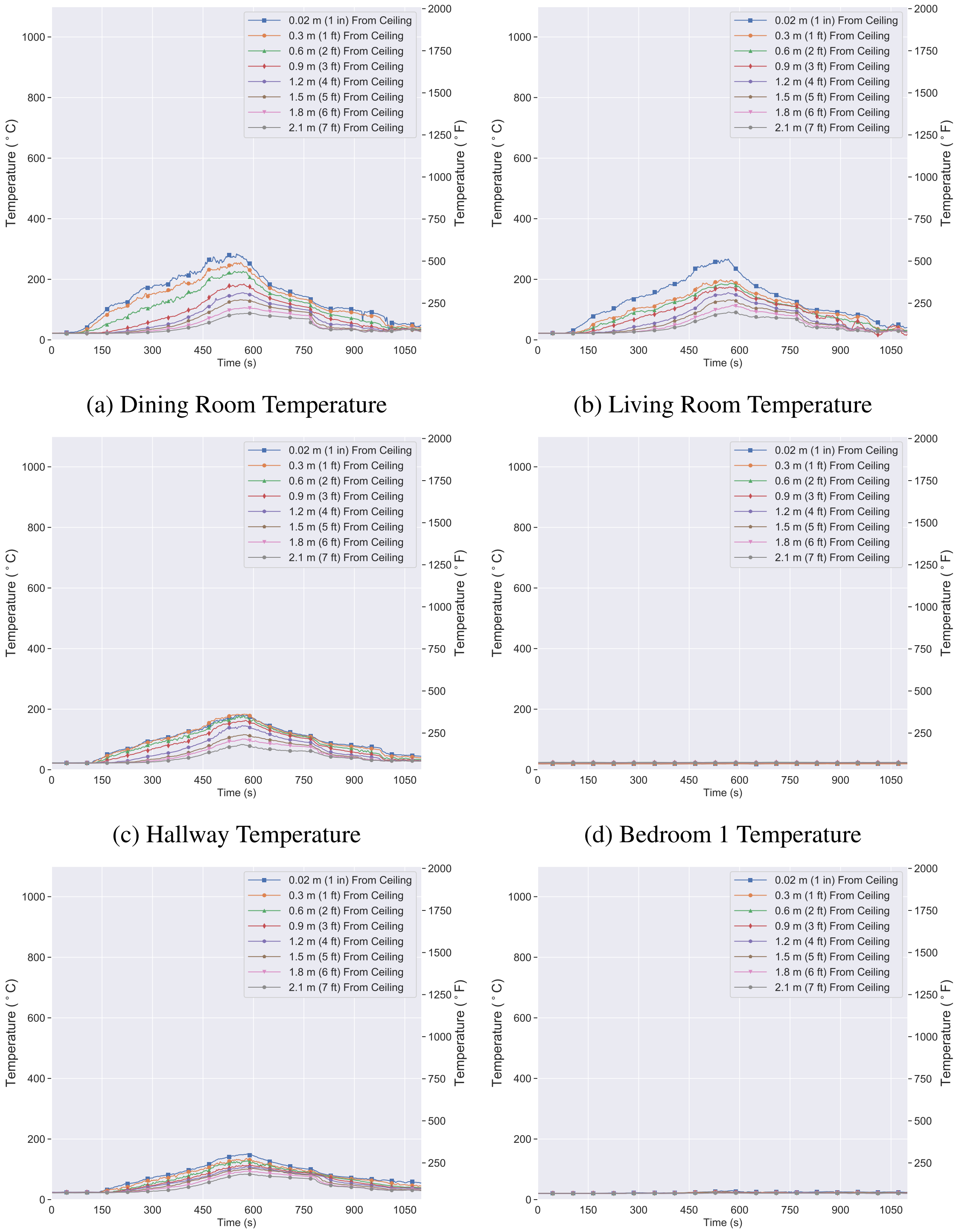


Figure 4.38: Experiment 8, no exterior ventilation openings, breakfast area temperatures versus time

Figure 4.39 shows the temperature histories for the thermocouple array locations inside the single story structure. The dining room, living room, hallway, and bedroom 2 areas were open to the kitchen/breakfast area, and as a result the temperature trends follow those of the breakfast area. The breakfast area (see Figure 4.38) and dining room thermocouple array (see Figure 4.39a) were the two closest arrays to the area of ignition and while the bedroom 2, living room, and hallway thermocouples were further away. Being remote from the kitchen resulted in reduced peak temperatures. The breakfast area temperature, which was closest to the kitchen ignition, reached approximately 300 °C (572 °F) at ceiling with cooler temperatures closer to the floor. The temperatures in the bedrooms with closed doors did not increase.



(a) Dining Room Temperature

(b) Living Room Temperature

(c) Hallway Temperature

(d) Bedroom 1 Temperature

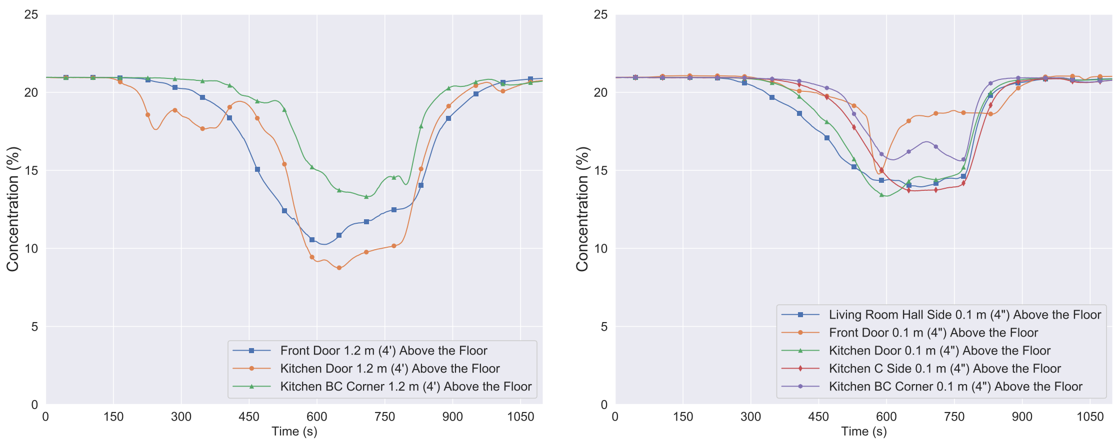
(e) Bedroom 2 Temperature

(f) Bedroom 3 Temperature

Figure 4.39: Experiment 8, no exterior ventilation openings, temperature time histories for all rooms.

Figure 4.40 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the ignition within the kitchen as well to include locations in the living room and front door. Three of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.40a), and the other five were positioned 100 mm (4 in.)above the floor (see Figure 4.40a). The four meter sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port.

The oxygen meters measuring conditions at the 1.2 m (4 ft) level started to decrease at 150 s with the most distinct drop in oxygen concentration in the kitchen and at the front door occurring at approximately 450 s. The oxygen meters that measured gases sampled at 1.2 m (4 ft) above the floor had minimum oxygen concentrations between 8.7%–13.3%. The oxygen meters that measured gases sampled at 100 mm (4 in.)had minimum oxygen concentrations of 13.3% or greater. The elevated fuel (0.9 m (3 ft) height) of the kitchen fire and low oxygen concentrations at the 1.2 m (4 ft) level combined with the closed front door closed resulted in a fire that self-extinguished



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.40: Experiment 8, no exterior ventilation openings, oxygen concentration versus time at 1.2 m and 0.1 m above the floor

The data from the velocity array in the hallway provides insight into the gas flow circulation into and out of bedroom 2, as shown in Figure 4.41. The gases flowing into the bedroom are shown with a positive velocity and gases out of the bedroom are shown with a negative velocity. When the fire was near its peak burning rate, more than the top half of the hallway had gases exhausting into the bedroom room at velocities of about 1 m/s (2.2 mph). At the same time denser, cooler gases were flowing into the living room, near the floor at about 1 m/s (2.2 mph). As the fire decreased in size, the exhaust gases began to slow. The middle of the hallway had a flow of roughly 0.8 m/s (1.8 mph).

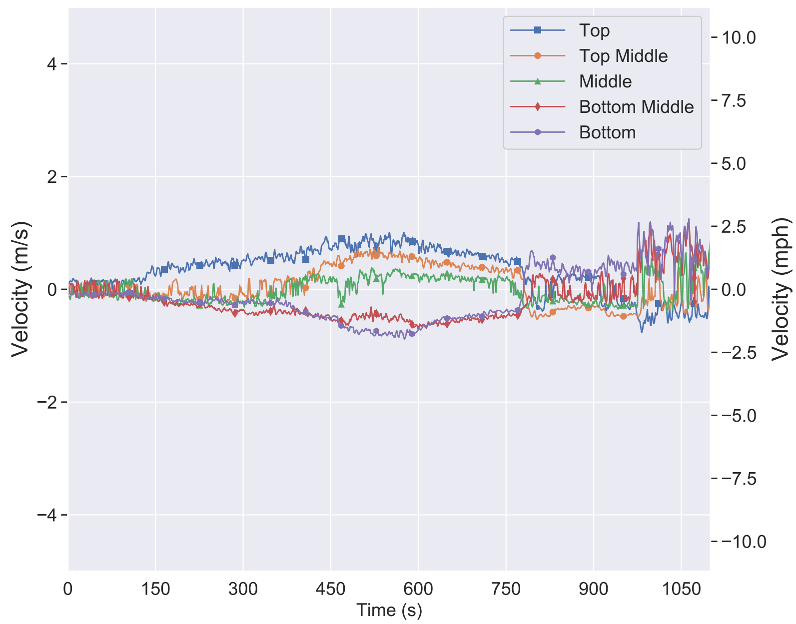
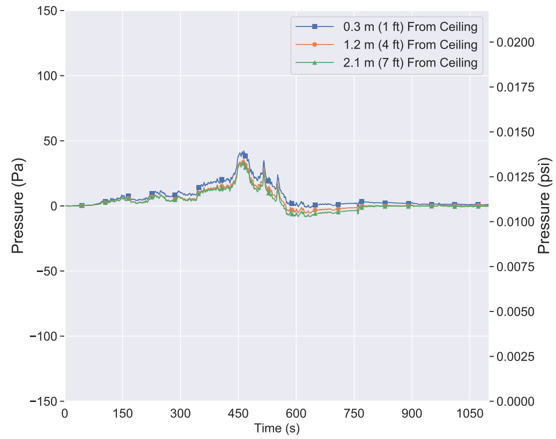
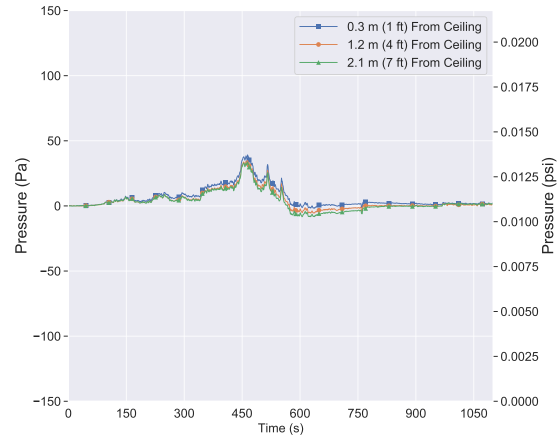


Figure 4.41: Experiment 8, no exterior ventilation openings, hallway velocity versus time. Positive pressure flowing from living room to bedroom 2.

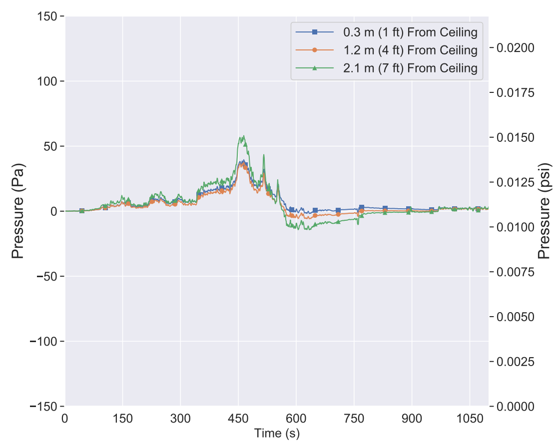
Figure 4.42 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. For the kitchen and rooms open to the kitchen (i.e., the dining room, living room, and bedroom 2), pressures peaked between 40–50 Pa due to the lack of exterior ventilation. The pressures peaked at similar times to the temperatures within the structure. The two bedrooms with closed doors showed no noticeable pressure change.



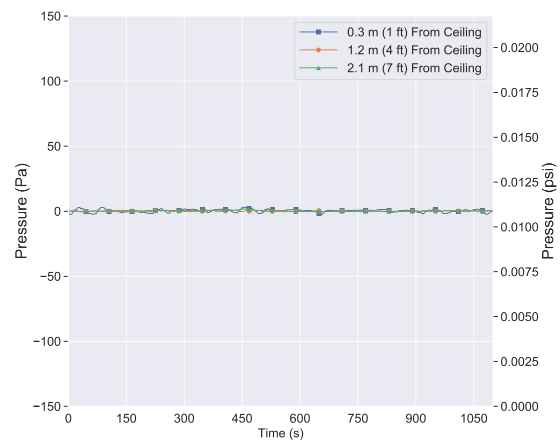
(a) Dining Room Pressure



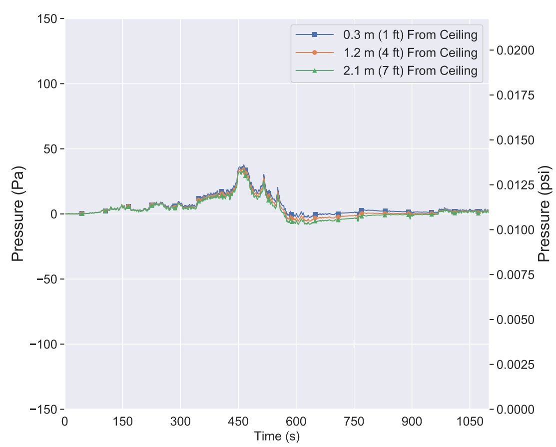
(b) Kitchen Pressure



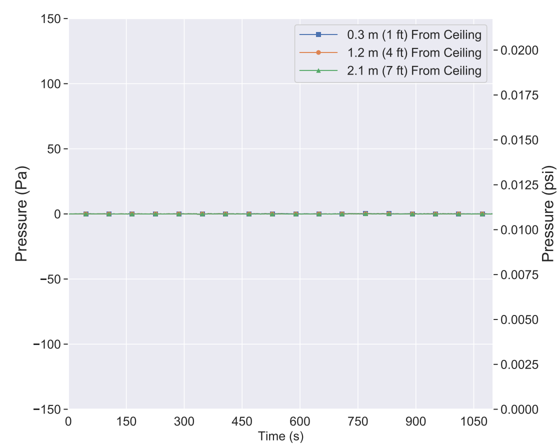
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.42: Experiment 8, no exterior ventilation openings, pressures in all rooms

4.2.2 Front Door Open

Experiments 10 and 11 were designed to be similar to experiments 6 and 8, except for one change in ventilation: an open front door. The front door was open for the duration of Experiment 10. In Experiment 11, the front door was closed after the fire developed in the kitchen to examine the change in fire behavior. All of the other exterior vents remained closed until the experiments were terminated.

Experiment 10

Similar to Experiments 6 and 8, the time of ignition was considered to be the time of the first observation of flames near the base of the coffee maker. Within a minute of the observation of flames, the fire had increased in size and impacted the bottom of the wall cabinet above the coffee maker. Less than two minutes after ignition, flames extended to the front and right side of the wall cabinet. Approximately 3 min after ignition a light gray colored smoke layer approximately 0.91 m (3 ft) below the ceiling had developed in the kitchen and spread into the living room as well as throughout the open areas of the structure. Twenty seconds later, flames spread from the area of origin to the kitchen ceiling. Over the course of the next minute, flames spread to the right of the area of origin to the cabinet over the range and to the left of the area of origin to the corner cabinet. As the fire in the kitchen increased in size, smoke flow out of the front doorway increased. The top quarter of the doorway exhausted dark gray smoke.

Radiant heat flux from the kitchen flames heated the kitchen floor to the point of auto-ignition at approximately 6 min and 45 s after ignition. Within 15 s of the floor igniting, the fire on the floor increased in size with flames approximately 0.9 m (3.3 ft) in height. The additional burning resulted in the increased depth of the visible smoke layer in the kitchen to 1.5 m (5 ft) below the ceiling. The thermal imager view of the kitchen doorway showed an increase in the velocity of the gases exiting the kitchen and entering the living room. The additional heat moving into the living room resulted in the heating of the carpeting on the living room floor. The neutral plane dropped in the front doorway as black smoke flow filled the upper half of the doorway.

At 7 min and 30 s after ignition, the visible hot gas layer had descended down to within 0.3 m (1 ft off the floor) in the kitchen and the living room. Black smoke filled the upper three-quarters of the front doorway. Eight minutes after ignition, the fire in the kitchen was obscured by smoke and appeared to have decreased in size. The velocity of the air entering and the hot gases exiting the front door increased. Between eight minutes and ten minutes after ignition, the neutral plane began to fluctuate. Initially, the neutral plane moved up 0.3 m (1 ft) or so in the doorway, which allowed additional air flow into the structure. Then the fire in the kitchen began to increase in size, which resulted in the carpeting in the living room igniting. This caused the neutral plane to drop back down.

Over the next two minutes the fire conditions in the kitchen appeared steady while the fire conditions in the living room continued to increase. Flames began to exit the upper portion of the front doorway at 12 min and 40 s after ignition, and the section of the living room between the kitchen and the open front door transitioned through flashover.

Firefighters started suppression through the front door, 13 min and 35 s after ignition. A time table of major events is included in Table 4.9.

Table 4.9: Timeline for Experiment 10, Kitchen Fire with an Open Front Door

Time (s)	Event
0	Ignition
60	Fire has extended to the bottom of the wall cabinet
120	Flames extended up the front and right side of the wall cabinet
180	Hot gas layer 0.91 m thick in kitchen
200	Flames reach the kitchen ceiling
260	Fire spread to the wall cabinets adjacent to the area of origin, dark gray smoke exhausted out of top quarter of front door
405	Ignition of the kitchen floor
420	Fire on kitchen floor increased, hot gas layer increased to 1.5 thick, black smoke exhausted out of top half of front door
450	Hot gas layer 2.1 m thick in kitchen, black smoke exhausted out of top three quarters of front door
480	Kitchen fire in decay
600	Kitchen fire steady, carpeting in living room near kitchen door ignited
760	Flames began to exit the front door
770	Living room flashover
815	Suppression

Figure 4.43 shows the temperature profile in the kitchen. At 180 s, the rise in the top three thermocouples shows the development of the hot gas layer in the kitchen. The top three thermocouples continued to rise in temperature as more energy was released from the fire. At approximately 405 s post ignition, the lower thermocouples all rose as the room transitioned to flashover, with temperatures all above 600 °C (1112 °F).

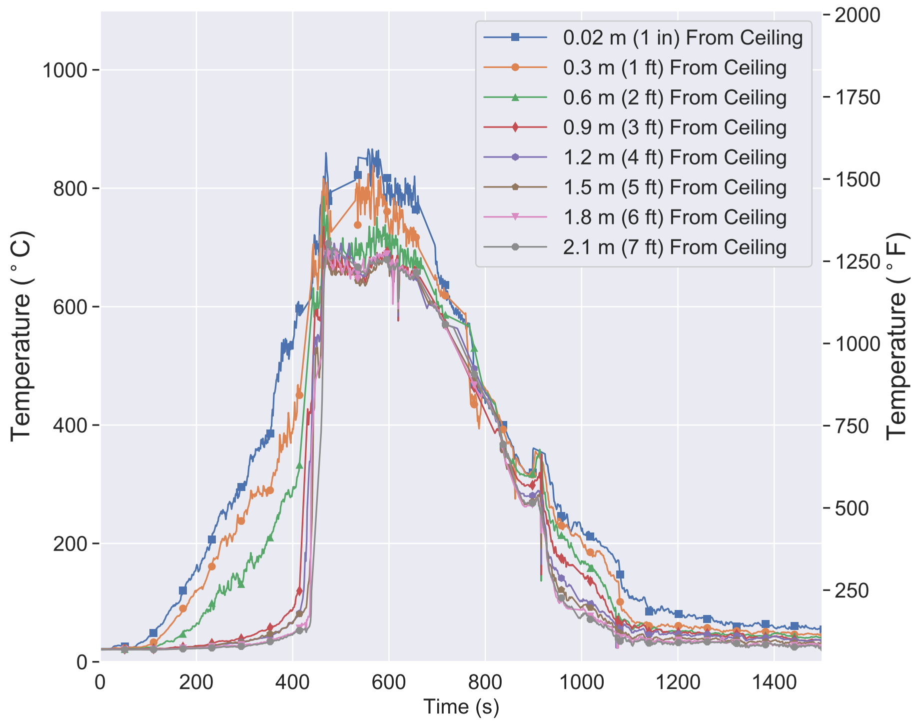


Figure 4.43: Experiment 10, front door open, kitchen versus time

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When the kitchen transitioned to flashover, the exhaust flow at front door was in pure exhaust as shown in Figure 4.44. Following that transient period of exhaust, the bottom two probes showed negative flow (intake), and the top two probes remained positive (exhaust). The bidirectional flow, with the middle probe fluctuating between intake and exhaust, remained until suppression.

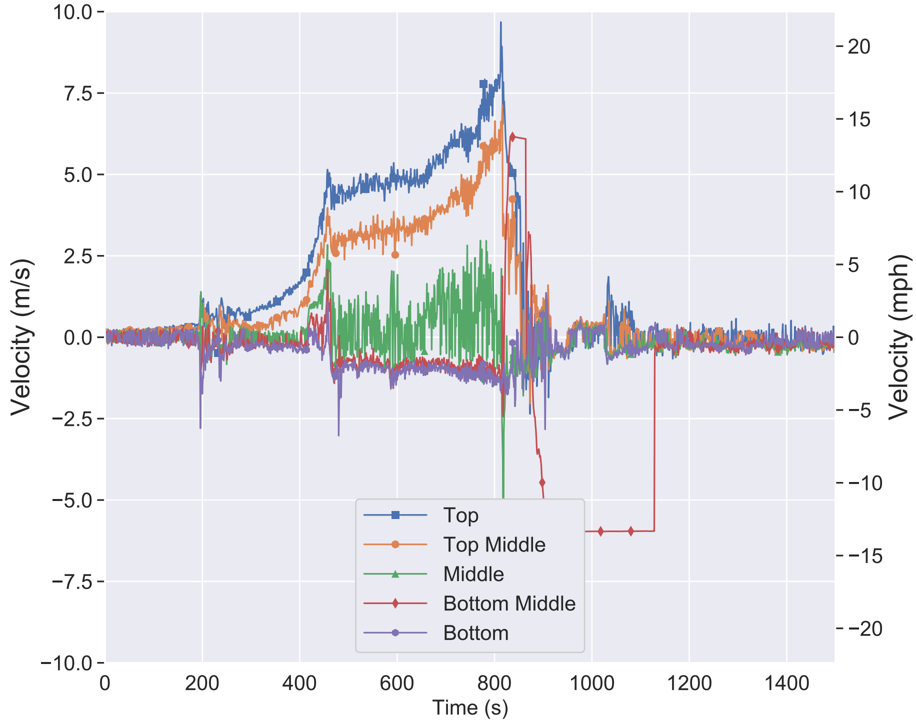

Figure 4.44: Experiment 10, front door open, front door velocity versus time.

Flames began to exit the upper portion of the front doorway at 12 min and 40 s after ignition. Figure 4.45 shows the front door thermocouples; specifically, the rise of the top two thermocouples when flames were observed at the front door.

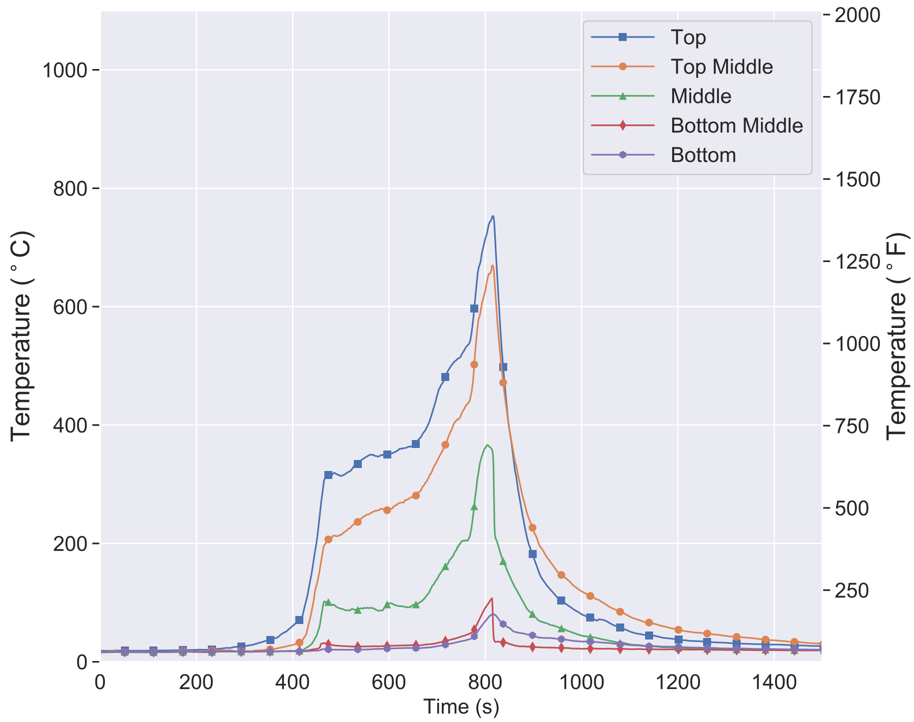

Figure 4.45: Experiment 10, front door open, front door temperature versus time
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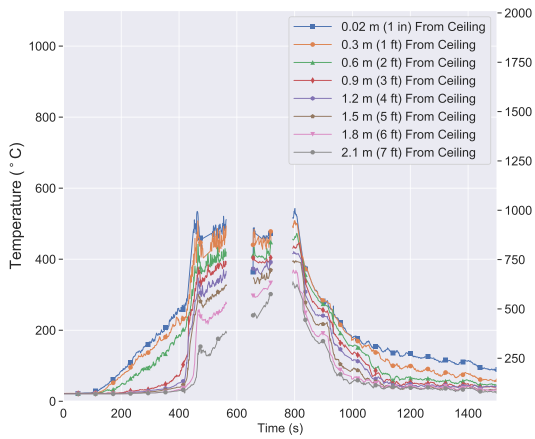
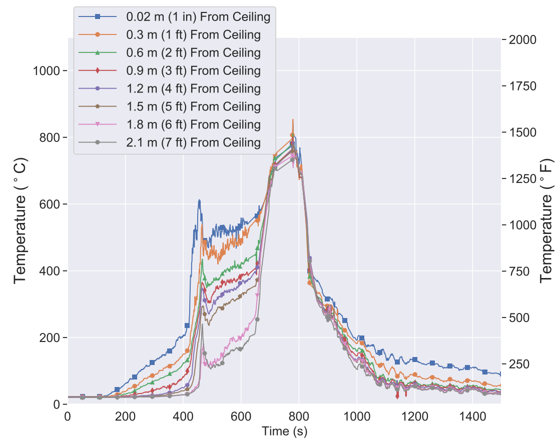
Figure 4.46 shows the temperature histories for the thermocouple array locations inside the single story structure. The dining room, living room, hallway, and bedroom 2 areas were open to the kitchen/breakfast area, and as a result the temperature trends follow those of the breakfast area. The living room (see Figure 4.46b) was between the kitchen (ignition) and the open front door (ventilation) and was the only room to have temperatures floor to ceiling in excess of 600 °C (1112 °F).

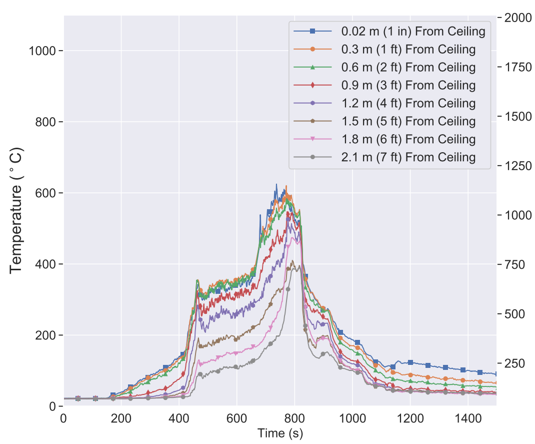
The remaining rooms open to kitchen (i.e., the dining room, hallway, and bedroom 2) showed similar temperature profiles, with less severe peaks as they were more remote from the ignition room. Note that in the dining room, there were two points in time where the thermocouple data was lost during the experiment. The temperatures in the bedrooms with with closed doors did not increase.



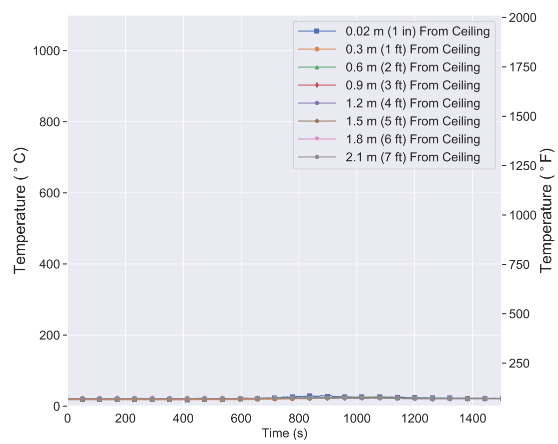
(a) Dining Room Temperature



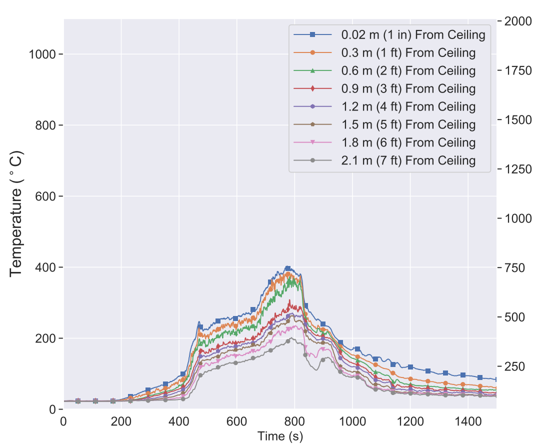
(b) Living Room Temperature



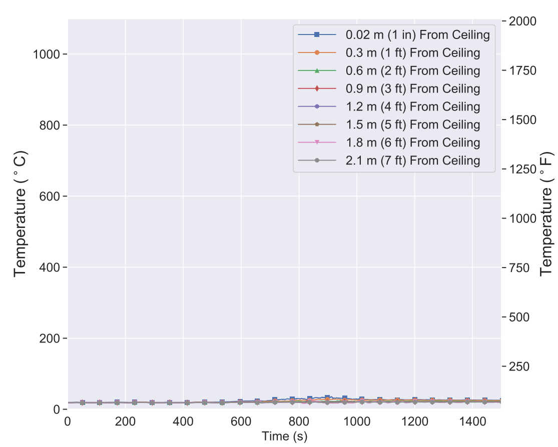
(c) Hallway Temperature



(d) Bedroom 1 Temperature



(e) Bedroom 2 Temperature



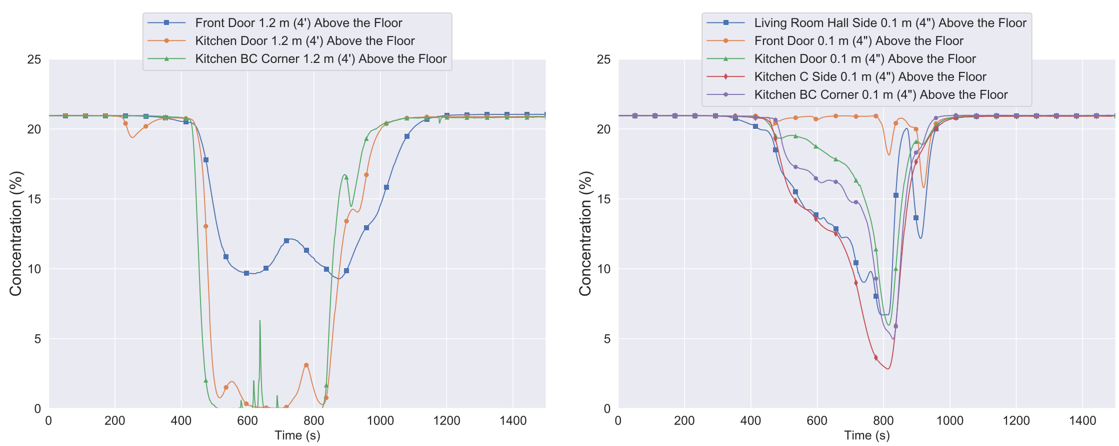
(f) Bedroom 3 Temperature

Figure 4.46: Experiment 10, front door open, temperature time histories for all rooms.

Figure 4.47 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the ignition within the kitchen and to include locations in the living room and front door. Three of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.47a) and the other five were positioned 100 mm (4 in.)above the floor (see Figure 4.47a). The four meter sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port.

The oxygen meters measuring conditions at the 1.2 m (4 ft) level dropped precipitously at approximately 450 s post ignition. Both sensors in the kitchen dropped to near 0% oxygen at the 1.2 m level. This confirms the earlier discussion that the smoke layer had dropped to 0.3 m (1 ft off the floor). Despite the open door, out flow at the doorway and consumption of oxygen in other parts of the structure prevented oxygen from reaching the kitchen. The 1.2 m (4 ft) sensor at the doorway dropped to 9.6% then rose to 12% before dropping back down to 9.2%, coinciding with the fluctuations of inflow/outflow at the middle doorway velocity probe.

The oxygen sensors at the 100 mm (4 in.)height, except for the front door probe, started to decrease at the same time at the 1.2 m (4 ft) level, but decreased at a much slower level. It was not until 780 s post ignition when the kitchen and living room were post-flashover that these sensors reached their minimum values between 2.9% and 6.8%. With the front door open, the oxygen at the 100 mm (4 in.)level remained near ambient until a drop to 18.2% when the living room was post flashover just prior to suppression actions.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.47: Experiment 10, front door open, oxygen concentration versus time at 1.2 m and 0.1 m above the floor.

The velocity array in the hallway provides insight into the gas flow circulation into and out of bedroom 2 (see Figure 4.48). The gases flowing into the bedroom show a positive velocity, and gases out of the bedroom are shown with a negative velocity. When the fire was near its peak burning rate, more than the top half of the hallway had gases exhausting into the bedroom at velocities of about 2.5 m/s (5 mph). At the same time, denser, cooler, gases near the floor were flowing into the living room at about 1.6 m/s (3.6 mph). As the fire decreased in size, the exhaust gases began to slow. Compared to Experiments 6 and 8, the pressure relief of the open front door allowed for increased flow through the hallway.

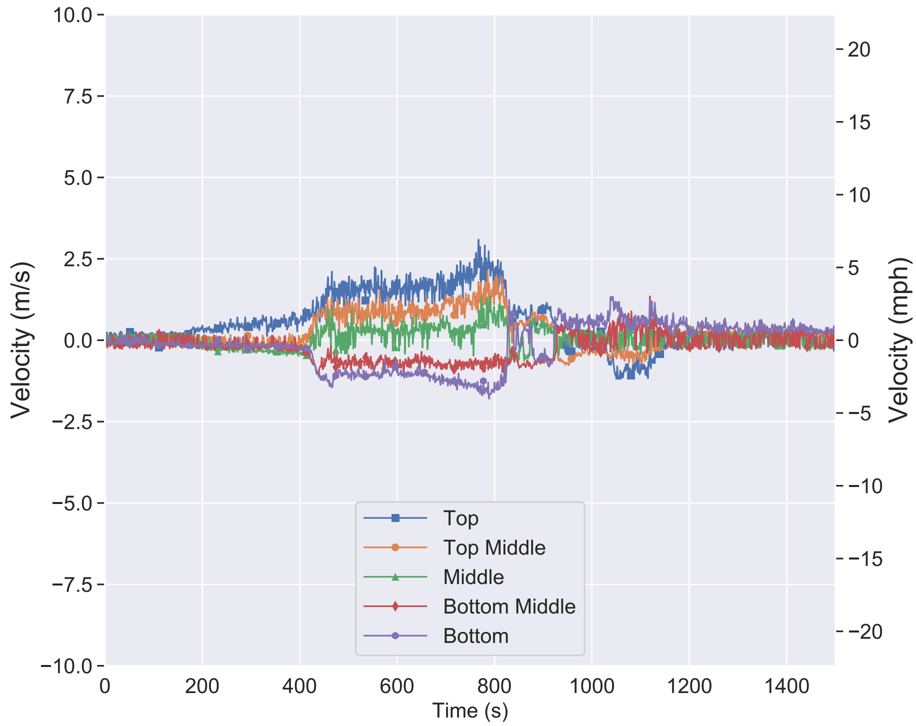
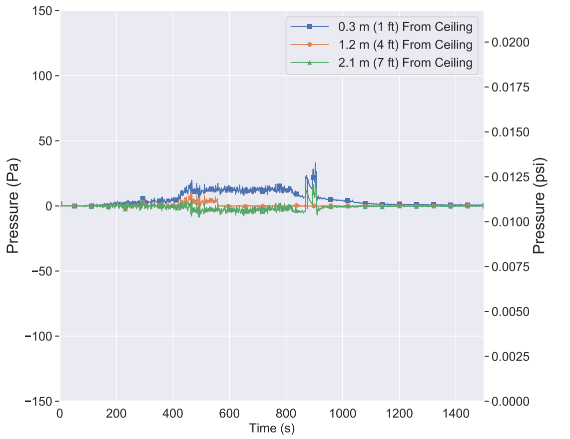
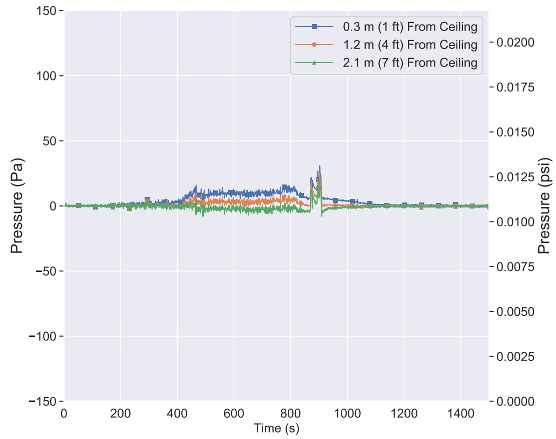


Figure 4.48: Experiment 10, front door open, hallway velocity versus time.

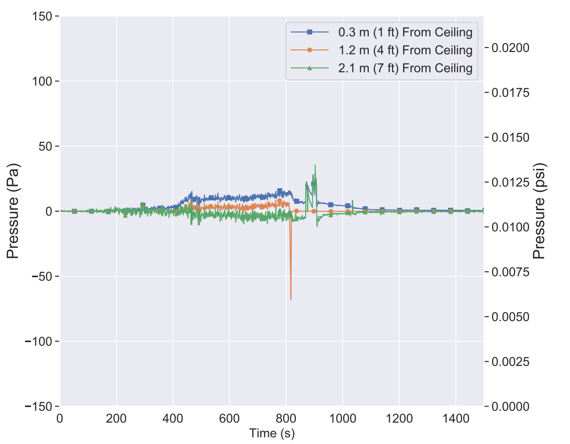
Figure 4.49 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. For the kitchen and rooms open to the kitchen (i.e., the dining room, living room, and bedroom 2), pressures peaked between 10–15 Pa due to the open front door. The two bedrooms with closed doors showed no noticeable pressure change.



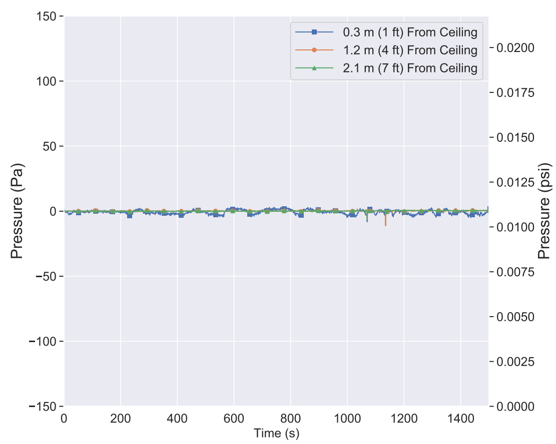
(a) Dining Room Pressure



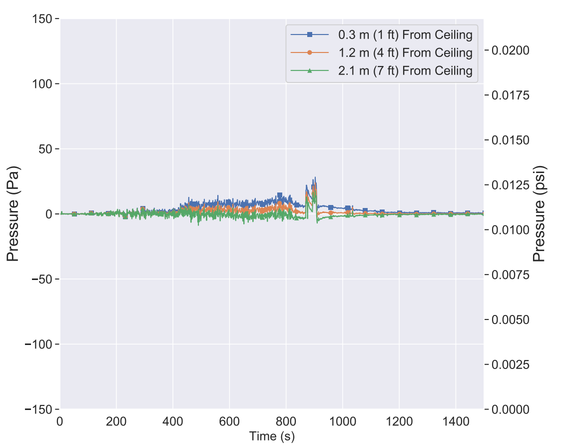
(b) Kitchen Pressure



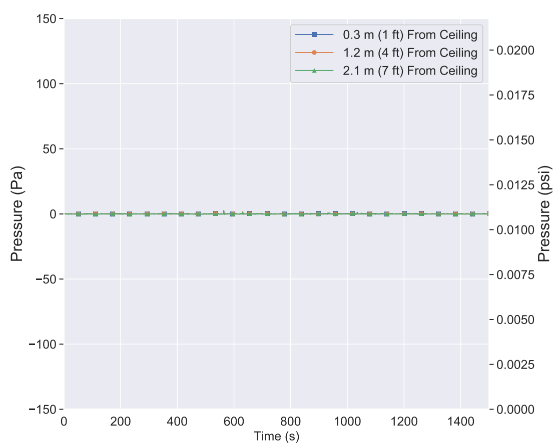
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.49: Experiment 10, front door open, pressures in all rooms.

Experiment 11

Experiment 11 used the same electrically modified coffee maker as Experiments 6, 8, and 10. The first coffee maker was energized, began to smoke, but did not ignite. Another modified coffee maker was installed on the kitchen countertop, and the test was re-started. Again the coffee maker was generated smoke but no flames. A firefighter then entered the kitchen with a lit propane torch. The torch ignited the smoke coming off of the coffee maker. The firefighter left the structure after ignition was confirmed. The kitchen fire developed in a manner similar to experiment 10.

Three minutes and fifteen seconds after ignition, the fire had increased in size and impacted the bottom of the wall cabinet above the coffee maker. Four minutes and twenty seconds after ignition, flames extended to the front and right side of the wall cabinet. Approximately five minutes and twenty seconds after ignition, a light gray colored smoke layer approximately 0.91 m (3 ft) below the ceiling had developed in the kitchen and spread into the living room as well as throughout the open areas of the structure. Over the course of the next two minutes, flames had spread to the right of the area of origin to the cabinet over the range and to the left of the area of origin to the corner cabinet. As the fire in the kitchen increased in size, smoke flow out of the front doorway increased. The top quarter of the doorway exhausted dark gray smoke.

Radiant heat flux from the kitchen flames heated the kitchen floor to the point of auto-ignition at approximately 7 min and 40 s after ignition. Within 20 s of the floor igniting, the hot gas layer was 2.1 m thick in kitchen and black smoke exhausted out of top 2/3 of front door. At this point, both the kitchen and breakfast area transitioned to flashover.

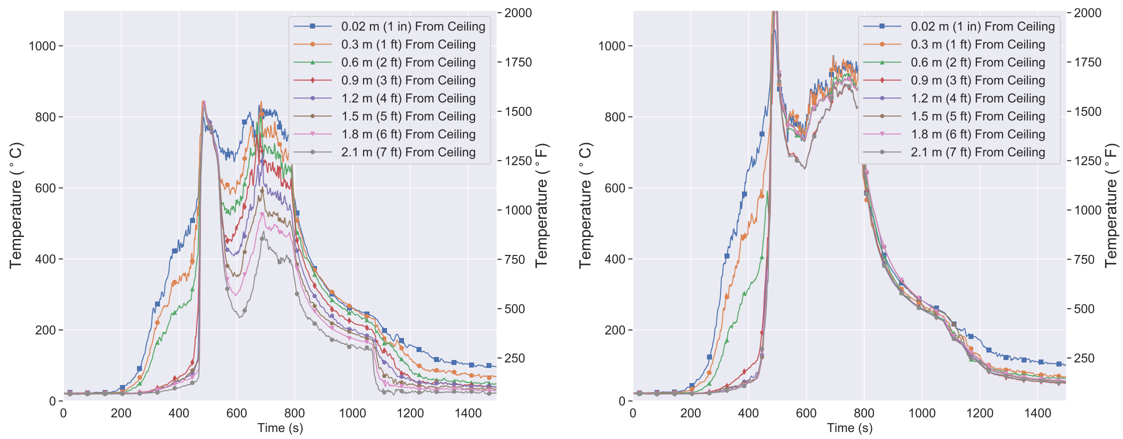
Eight minutes after ignition, the fire in the kitchen was obscured by smoke and appeared to have decreased in size. The velocity of the air entering and the hot gases exiting the front door increased. Between eight minutes and twelve minutes after ignition, the neutral plane began to fluctuate. Initially, the top two-fifths of the doorway was in exhaust, which allowed additional air flow into the structure. Then the fire in the kitchen began to increase in size, which resulted in the carpeting in the living room igniting. This caused the neutral plane to drop to halfway in the doorway.

As the fire began to move into the living room, 13 min after ignition the front door was closed. Closing the front door cut off the flow of air to the fire and suppressed the fire. Firefighters reopened the kitchen door just prior 18 min post-ignition. There was no rekindle, and water was applied to local hot spots. A time table of major events is included in Table 4.10.

Table 4.10: Timeline for Experiment 11, Kitchen Fire with an Open Front Door

Time (s)	Event
0	Ignition of gases emitted by coffeemaker with torch
180	Foam cups and chips ignited from coffeemaker flames
195	Fire has extended to the bottom of the wall cabinet
260	Flames extended under cabinet and up the front and right side of the wall cabinet
320	Flames reach the kitchen ceiling, a hot gas layer 0.91 m thick forms in kitchen
440	Fire has spread to the wall cabinets adjacent to the area of origin, dark gray smoke exhausted out of top quarter of the front door
460	Ignition of the kitchen floor
470	Fire on kitchen floor increased, hot gas layer increased, black smoke exhausted out of top half of the front door
480	Hot gas layer 2.1 m thick in kitchen, black smoke exhausted out of top two-thirds of the front door
490	Kitchen fire in decay
600	Heat increasing in kitchen
660	Furniture in breakfast area adjacent to kitchen ignited
720	Kitchen fire steady, carpeting in living room near kitchen door ignited
770	Flames spread on carpeting toward front door, living room hot gas layer increasing in temperature
785	Front door closed to examine impact of stopping air flow to fire
1069	Kitchen doors opened, no rekindle, water applied to hot spots

Similar to Experiment 10, a hot gas layer developed in the kitchen, leading to a rise in temperature at the ceiling. As the fire grew, more energy was released and temperatures continued to increase. At 460 s after ignition, the kitchen floor had ignition, and shortly after this point, both the kitchen and breakfast area transitioned to flashover, as shown in Figure 4.50. Both rooms showed a decay in temperature as the kitchen became fuel rich, but as the oxygen subsequently recovered because of the open front door, temperatures increased and remained elevated until the front door was closed.



(a) Kitchen Temperature

(b) Breakfast Area Temperature

Figure 4.50: Experiment 11, front door open, kitchen (top) and breakfast area (bottom) temperatures versus time.

As the fire developed, there initially was full exhaust flow at the front door, followed by outflow at the top two probes, inflow at the bottom two probes, and fluctuations between inflow and outflow at the middle probe in Figure 4.51. Closing the front door 785 s after ignition cut off the flow of air to the fire, and in effect, suppressed the fire. This is shown by the sharp return to zero velocity in the doorway probes in Figure 4.51.

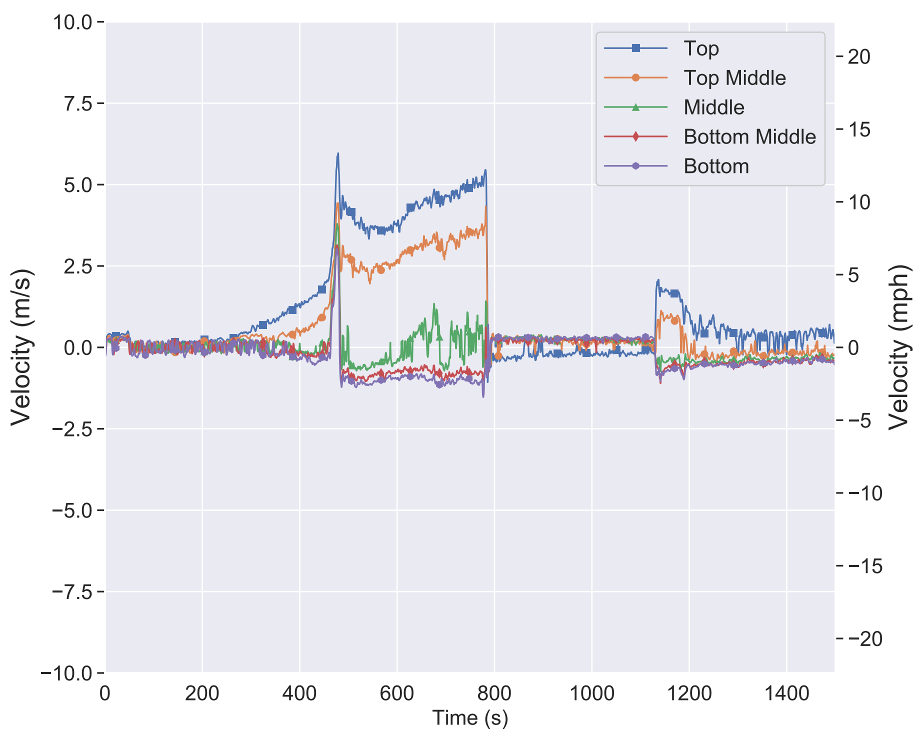
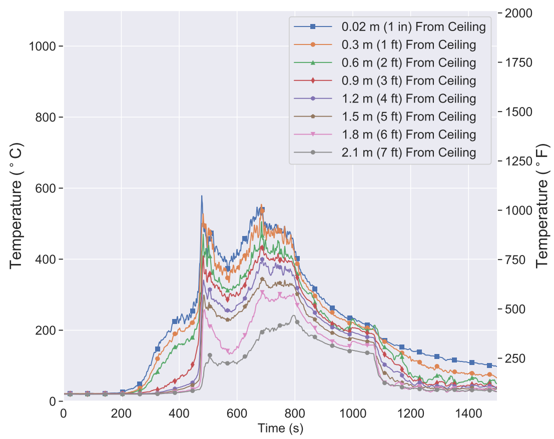
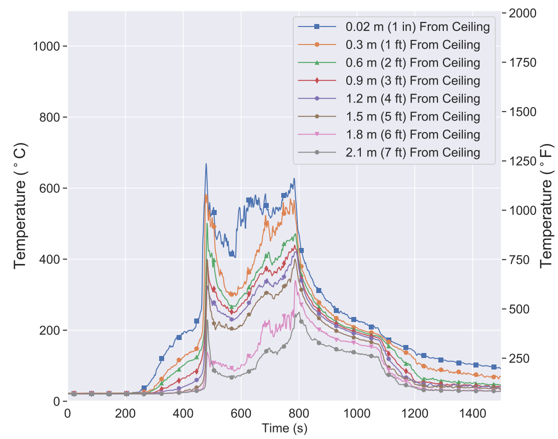


Figure 4.51: Experiment 11, front door open, front door velocity versus time.

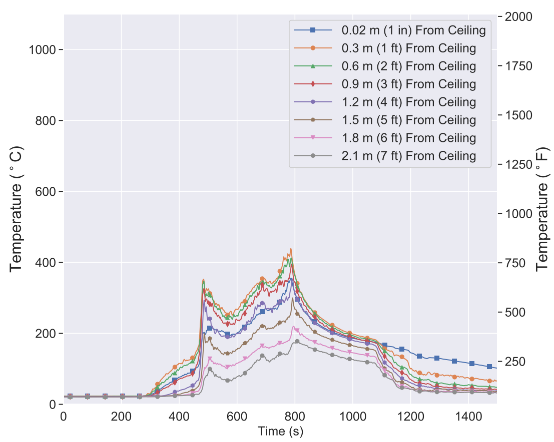
Figure 4.52 shows the temperature histories for the thermocouple array locations inside the single story structure. The dining room, living room, hallway, and bedroom 2 areas were open to the kitchen/breakfast area, and as a result the temperature trends follow those of the breakfast area. The living room (Figure 4.52b) was between the kitchen (ignition) and the open front door (ventilation), and while temperatures approached 600 °C (1112 °F) from floor to ceiling (an indication of a transition to flashover), the front door closure at 785 s post ignition resulted in a drop in temperature. The remaining rooms open to kitchen (i.e., the dining room, hallway, and bedroom 2) showed similar temperature profiles, with less severe peaks as they were more remote from the ignition room. The temperatures in the bedrooms with closed doors did not increase.



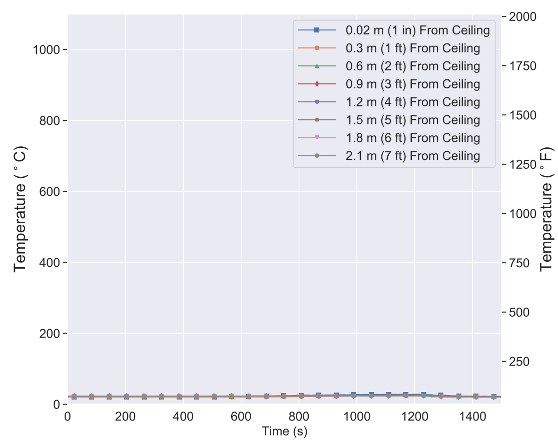
(a) Dining Room Temperature



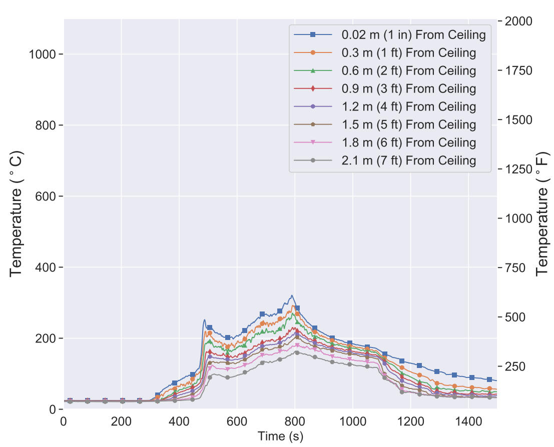
(b) Living Room Temperature



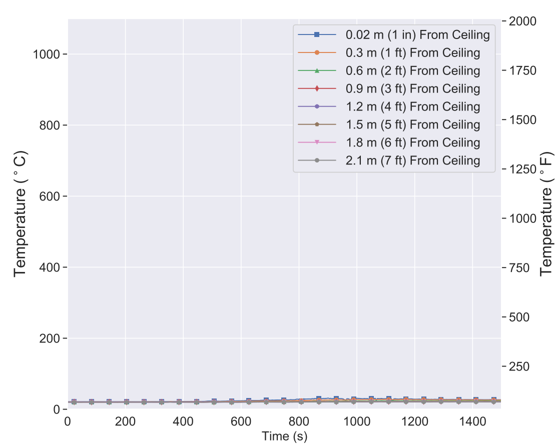
(c) Hallway Temperature



(d) Bedroom 1 Temperature



(e) Bedroom 2 Temperature

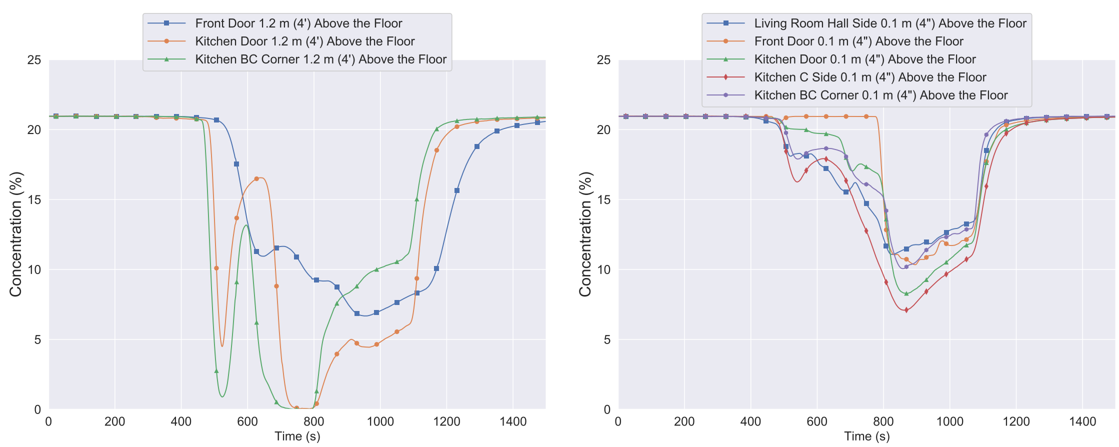


(f) Bedroom 3 Temperature

Figure 4.52: Experiment 11, front door open, temperature time histories for all rooms.

Figure 4.53 includes the time history of the eight oxygen meters. The sampling ports were positioned to surround the ignition within the kitchen and to include locations in the living room and front door. Three of the sampling ports were positioned at 1.2 m (4 ft) above the floor (see Figure 4.53a), and the other five were positioned 100 mm (4 in.)above the floor (see Figure 4.53a). The four meter sampling from 1.2 m (4 ft) above the floor measured a decrease in oxygen as soon as the hot gas layer covered the sampling port.

The oxygen meters measuring conditions at the 1.2 m (4 ft) level dropped precipitously at approximately 460 s post ignition. The oxygen concentrations in the kitchen dropped to near 0% oxygen at the 1.2 m level. This confirms the earlier discussion that the smoke layer had dropped to 0.3 m (1 ft off the floor). At approximately 530 s, the oxygen concentrations recovered to between 13% and 16% as the fire decayed in the kitchen. The influx of oxygen led to the fire regrowth, the rise in temperatures through the structure, and subsequent oxygen decay. The 1.2 m (4 ft) sensor at the doorway dropped slower than the kitchen sensors and reflects the observed behavior of the layer height at the doorway. The oxygen eventually dropped as low as 6.6% following the front door closure. The oxygen sensors at the 100 mm (4 in.) height, except for the front door probe, started to decrease at the same time at the 1.2 m (4 ft) level, but decreased at a much slower rate. It was not until the front door closed at 785 s that the sharp drop occurred in all measurements at the 100 m (4 in.) level.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.53: Experiment 11, front door open, oxygen concentration versus time at 1.2 m (top) and 0.1 m (bottom) above the floor

Figure 4.54 shows gas flow circulation velocities in the hallway between the living room and bedroom 2. The gases flowing into the bedroom show a positive velocity, and gases out of the bedroom show with a negative velocity. When the fire was near its peak burning rate, more than the top half of the hallway had gases exhausting into the bedroom room at velocities of about 2.0 m/s (4.4 mph). At the same time, denser, cooler gases near the floor were flowing into the living room at about 1.0 m/s (2.2 mph). As the fire decreased in size, the exhaust gases began to slow. Compared to Experiments 6 and 8, the pressure relief of the open front door allowed for increased flow through the hallway. It is important to note that unlike the front door where velocities dropped to zero when the door was closed, there was still flow through the hallway but with lower magnitude.

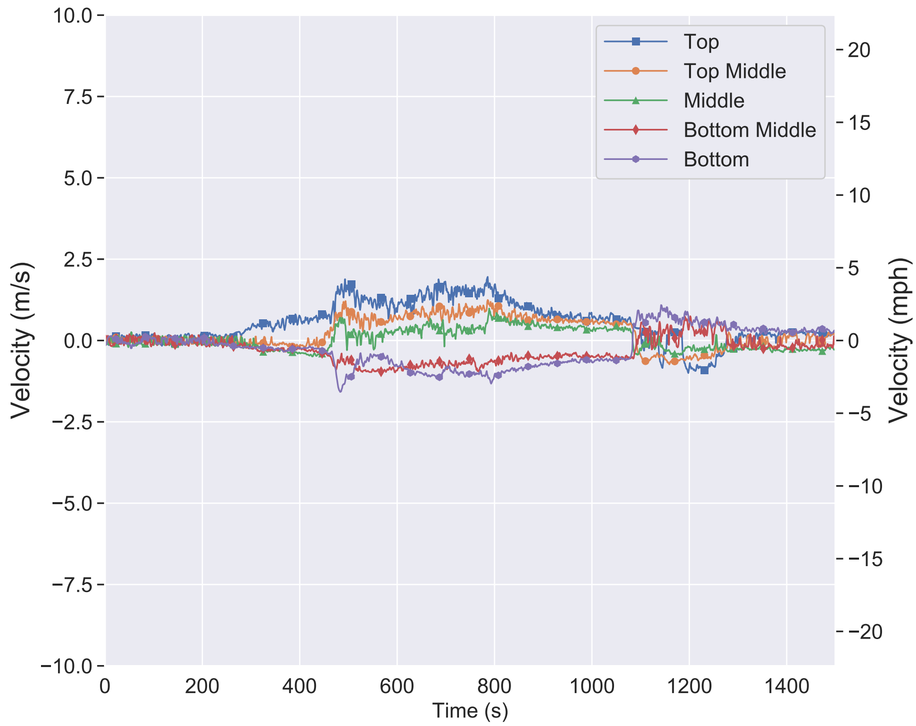
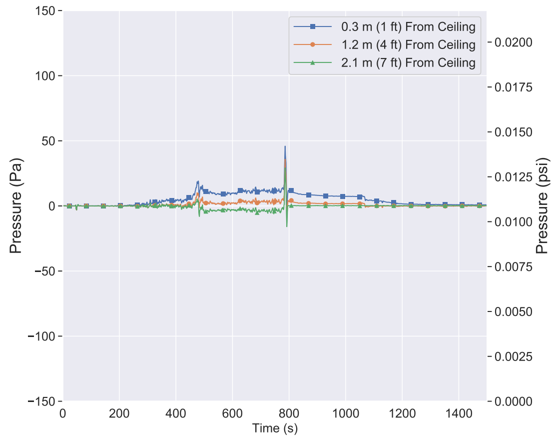
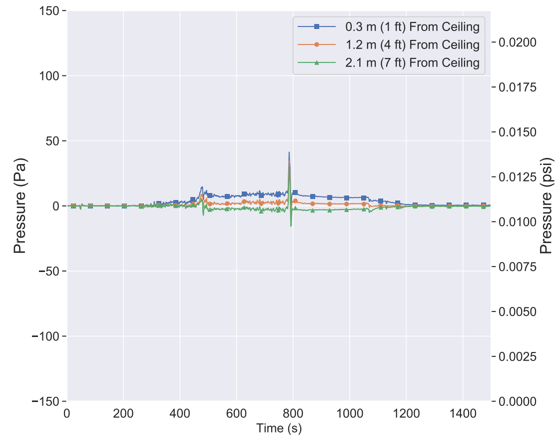


Figure 4.54: Experiment 11, front door open, hallway velocity versus time.

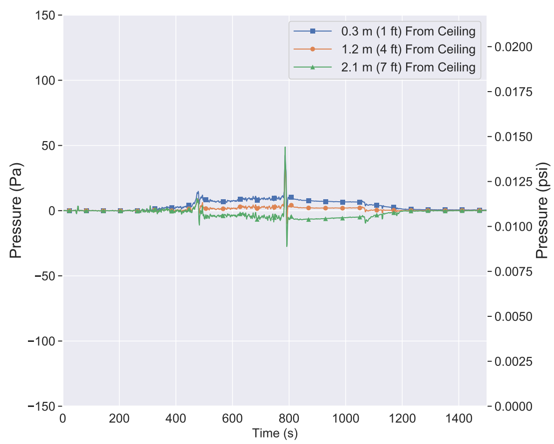
Figure 4.55 provides pressure time histories for all six rooms in the house. As the fire and the hot gas layer grew, the pressure levels throughout the structure increased. For the kitchen and rooms open to the kitchen (i.e.,the dining room, living room, and bedroom 2), pressures peaked around 10 Pa due to the open front door. The two bedrooms with closed doors showed no noticeable pressure change. The spike in the open rooms occurred as a result of the overpressure due to the front door getting closed.



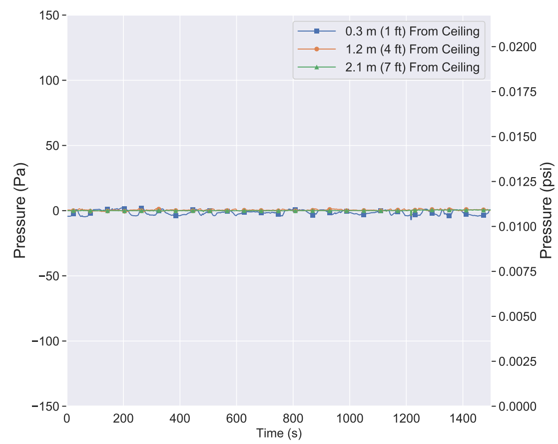
(a) Dining Room Pressure



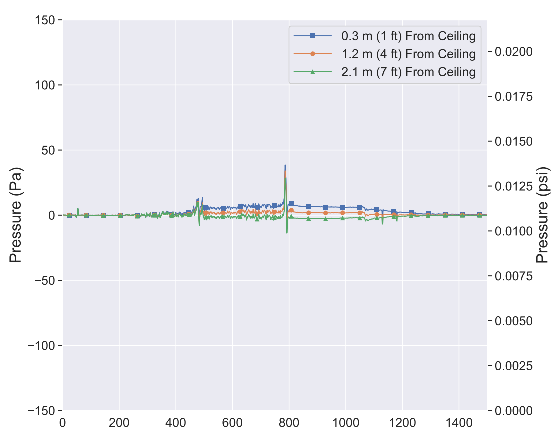
(b) Kitchen Pressure



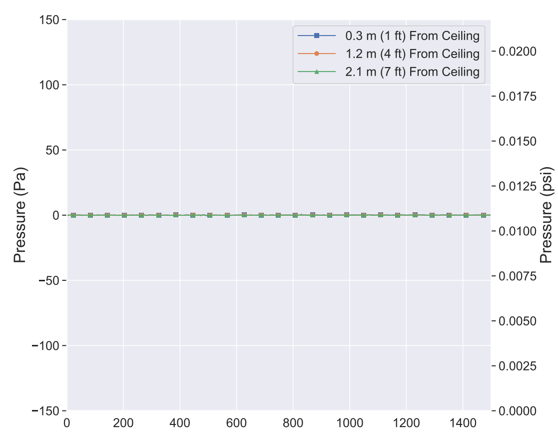
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.55: Experiment 11, front door open, pressures in all rooms.

4.3 Bedroom 1 Fires

4.3.1 All Exterior Vents Closed

Experiment 7

The fire was ignited in the plastic waste container next to the bed with an electric match. The fire grew on and above the bed near the origin. Within two minutes after ignition, the fire near the area of ignition continued to grow, and a hot gas layer had formed in all rooms open to the fire. During the next 60 s, the fire had spread along the head of the bed and to the adjoining nightstand. The hot gas layer in the living room was approximately 0.9 m (3 ft) deep. By 210 s after ignition, flames spread across the ceiling of bedroom 1. During the next 30 s, the base of the fire had spread across the top and right side of the bed. The hot gas layer in the kitchen was 1.8 m (5.9 ft) thick and the hot gas layer in the living room was 1.5 m (5.0 ft) thick.

The gases from the carpeting surrounding the bed were burning at 4 min after ignition. Smoke exited the structure around the window and door gaps. Within the next 10 s, the bedroom appeared to transition through flashover, and high velocity gases were observed exiting the bedroom door. At four minutes and 30 s after ignition, the hot gas layer was down to floor level throughout the open rooms in the structure, and black smoke was exhausting out of the gap between the door and the threshold. Five minutes after ignition, the fire in bedroom 1 had decreased in size, and within the next 30 s the smoke flow exiting the structure started to decrease. At 390 s after ignition, the fire had darkened down and light gray smoke was leaking out around the closed bedroom window shutters. Over the course of the next 90 s, the smoke flow around the front door and the bedroom window shutters stopped. Fifteen minutes after ignition, the firefighters ventilated the structure. Upon entry, no flames were evident in the structure. Table 4.11 provides a timeline of events for Experiment 7.

Table 4.11: Timeline for Experiment 7, Bedroom 1 Fire with all Exterior Vents Closed

Time (s)	Event
0	Ignition in plastic waste container next to bed
60	Flames on and above the corner of bed near the area of origin, smoke flowing from bedroom into living room
120	Fire growing in the bedroom, HGL building in all open rooms
180	Fire growing along the head of the bed and the area of the night stand, HGL in the living room is 0.9 m deep
210	Flames burning across the ceiling of bedroom 1, large volume of light gray smoke is pushing out of the gaps around the bedroom window closest to the head of the bed, lesser amounts of smoke flowing from gaps of other exterior openings
225	Flames spread across the top and right side of the bed, transition through flashover is occurring, HGL in living room is 1.5 m thick, and in the kitchen it is 1.8 m thick
240	Carpeting surrounding bed is burning, smoke exiting structure around window and door gaps increased
250	Nothing but fire showing in the bedroom, high velocity gases exiting bedroom door, appears to be near peak burning rate
270	HGL down to the floor throughout structure, black smoke exhausted out of gap between front door and threshold
300	Fire in bedroom 1 appears to be decreasing in size
330	Smoke flow exiting the structure has started to decrease
390	Fire has darkened down, light gray smoke still exiting around bedroom windows, black smoke exiting around front door
435	Smoke flow from the front door has stopped
480	Smoke flow from the bedroom window has stopped
900	Firefighters begin ventilation of structure, no flames are evident in the structure
1500	No rekindle

Figure 4.56 shows the temperatures versus time from the thermocouple array in bedroom 1. The temperatures show the development of the hot gas layer for the first 200 s after ignition, followed by the transition through flashover and temperatures from the ceiling down to the floor in excess of 600 °C (1112 °F). The peak temperatures were approximately 750 °C (1382 °F) at 250 s after ignition. Over the next 350 s, the temperatures had decreased to approximately 400 °C (752 °F). Temperatures in the bedroom continued to decrease and began to stratify. This process continued after the ventilation of the structure started at 900 s after ignition.

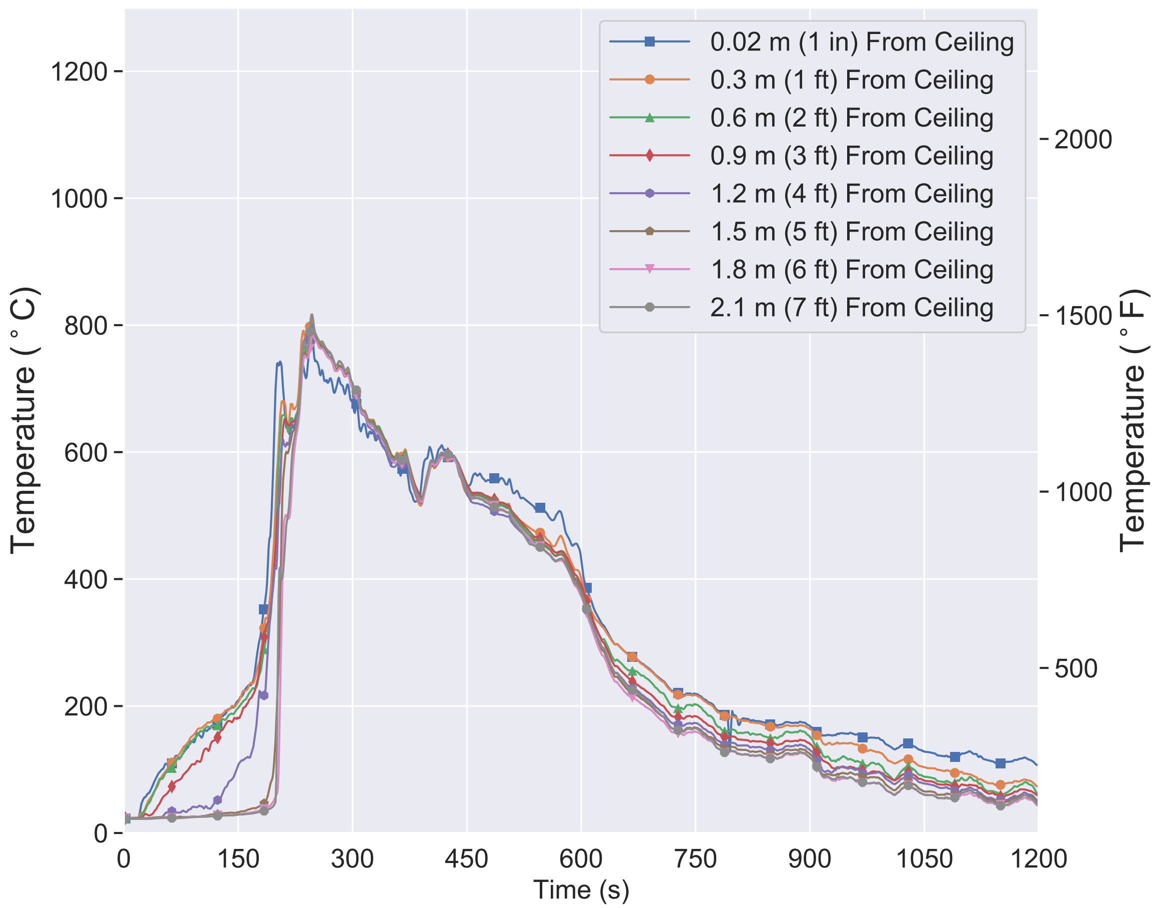
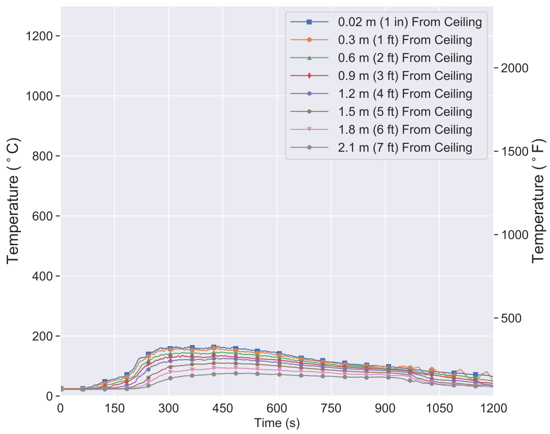
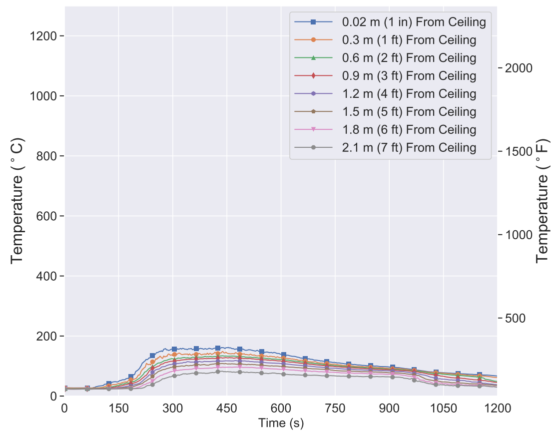


Figure 4.56: Experiment 7, no exterior ventilation openings, bedroom 1 temperatures versus time.

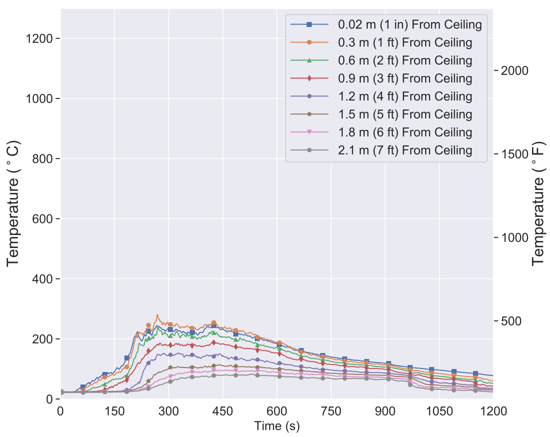
The temperature data from the other thermocouple arrays in the structure are presented in Figure 4.57. The hallway thermocouple array (see Figure 4.57c) was located closest to bedroom 1 and therefore had the highest temperatures of the adjacent spaces. The hallway area did not flashover. As the distance between the fire room and the thermocouple array increased, the peak temperatures decreased. Bedroom 3 was closed, which resulted in a negligible increase in temperature.



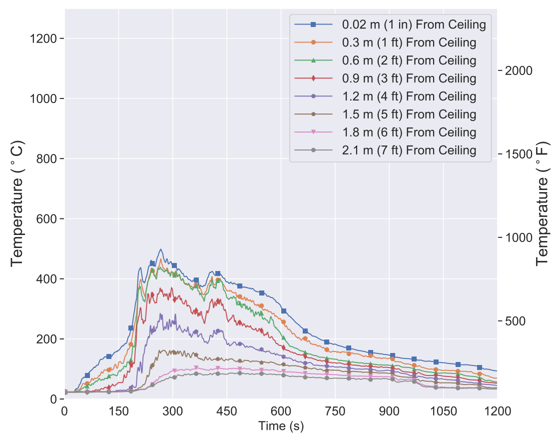
(a) Dining Room Temperature



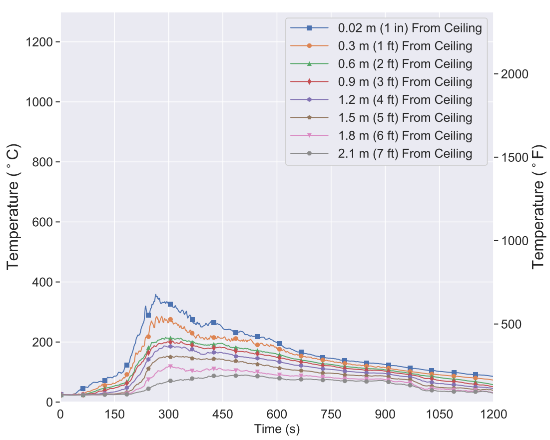
(b) Kitchen Temperature



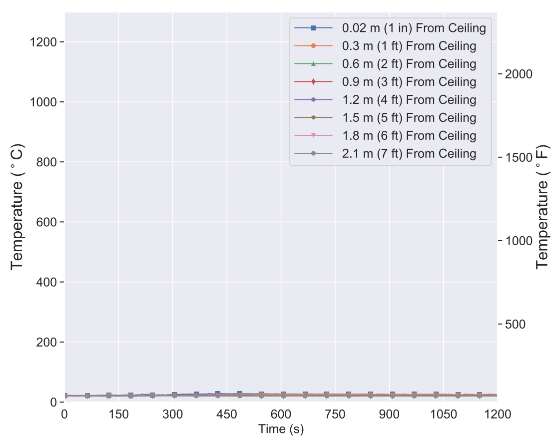
(c) Living Room Temperature



(d) Hallway Temperature



(e) Bedroom 2 Temperature

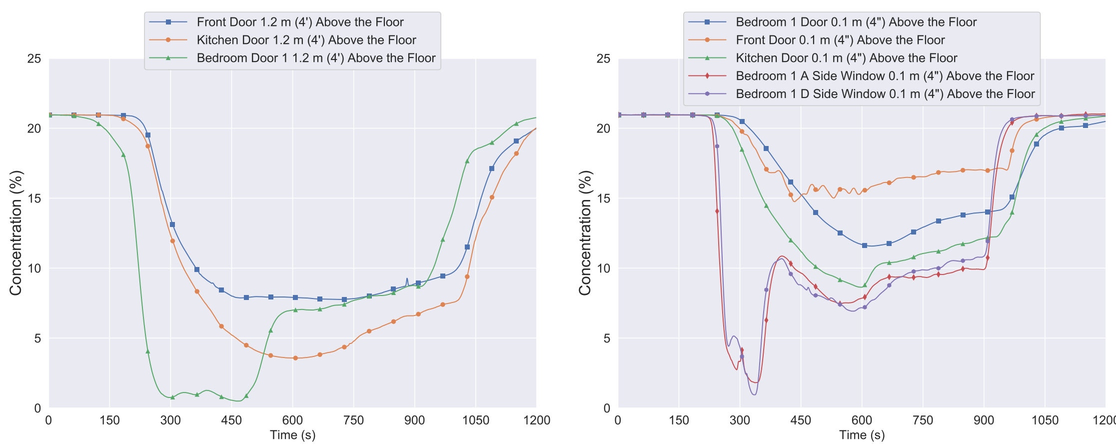


(f) Bedroom 3 Temperature

Figure 4.57: Experiment 7, no exterior ventilation openings, temperature time histories for all rooms.

Figure 4.58 shows the oxygen concentrations at different locations in the structure at two different elevations: 1.2 m (4 ft) above the floor and 0.1 m (4 in) above the floor. The top graph has three 1.2 m (4 ft) positions, one located just inside the bedroom 1 doorway, another in the doorway from the living room to the kitchen, and one adjacent to the closed front door. The oxygen level inside the bedroom decreased to near zero at about the time of peak temperatures. The oxygen concentrations at the other two locations decreased below 15% just as the temperatures in the bedroom had begun to decrease, which correlated with the observation that the fire size had also decreased.

In addition to three locations listed for the 1.2 m (4 ft) positions, five additional sample probes were added at the 0.1 m (4 in) above the floor level. Three oxygen sample probes were located in bedroom 1, one below each window and one at the doorway. The two probes near the floor below the windows in bedroom 1 exhibited the lowest oxygen concentrations. This would denote the area of flaming combustion in the room. The lower oxygen probe near the open bedroom door remained above 20% while the fire in the bedroom was growing and oxygen from the rest of the structure was drawn toward the fire room. As smoke was pushed into the adjoining open areas of the structure, the oxygen concentration in the room decreased faster than the bedroom doorway location. The oxygen levels in the bedroom decreased below 15% and remained there until after ventilation was started. The fire self-extinguished due to a lack of oxygen.



(a) Oxygen at 1.2 m Above Floor (b) Oxygen at 0.1 m Above Floor

Figure 4.58: Experiment 7, no exterior ventilation openings, oxygen concentration versus time at 1.2 m (top) and 0.1 m (bottom) above the floor.

The velocity array in the hallway provided some insight on the gas flow circulation into and out of bedroom 1. Figure 4.59 shows the gases flowing out of the bedroom with a positive velocity and gases flowing into the bedroom with a negative velocity. When the fire was near its peak burning rate, more than the top half of the doorway had gases exhausting into the hallway at velocities of about 2 m/s (4.4 mph). At the same time, denser, cooler, gases were flowing into the bottom of the doorway at about 1 m/s (2.2 mph). As the fire decreased in size, the exhaust gases began to slow. Exhaust flow was reduced to only the upper third of the hallway. The remainder of the hallway elevation served as a supply of cooler gases. It would appear, based on the hallway velocities, the oxygen concentrations, and the rate of temperature decrease, that flaming combustion had ceased just prior to 10 min after ignition.

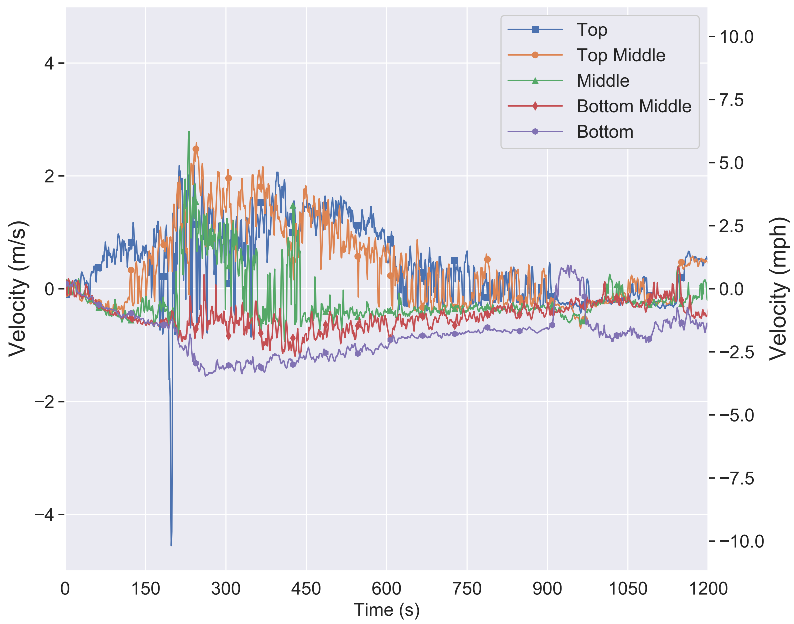
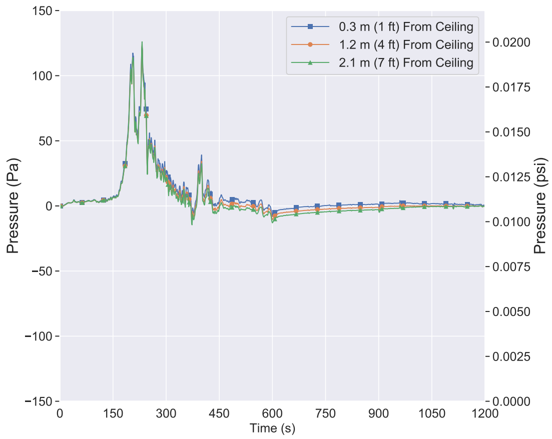
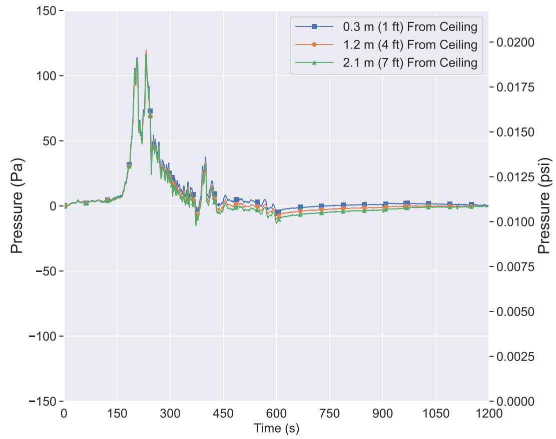


Figure 4.59: Experiment 7, no exterior ventilation openings, hallway velocity versus time. Positive velocity flowing from bedroom to living room.

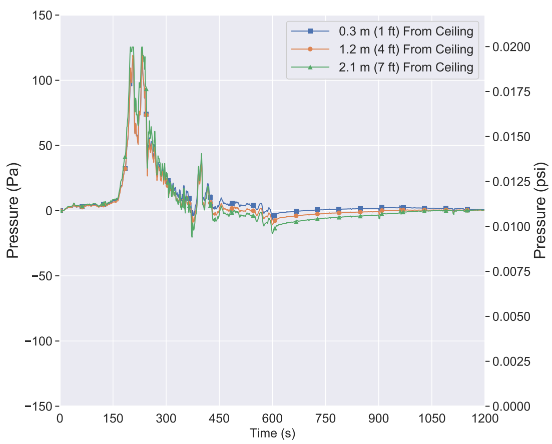
Pressures inside the structure at locations open to the fire room were similar, as shown in Figure 4.60. Pressures near the ceiling were slightly higher than the pressures near the floor, which accounts for the convective circulation in and out of bedroom 1. Bedroom 3, which was closed off from the rest of the structure, did not have a noticeable change in pressure. Note that the 1.2 m (4 ft) below the ceiling pressure sensor in bedroom 1 failed as the fire started to enter the decay stage (Figure 4.60d).



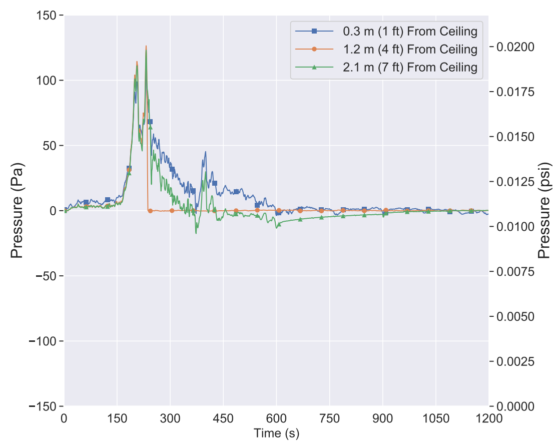
(a) Dining Room Pressure



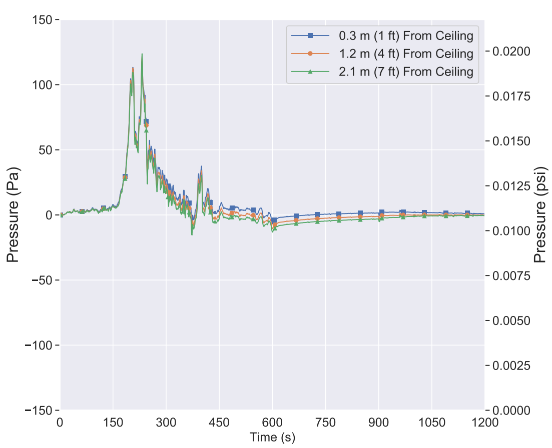
(b) Kitchen Pressure



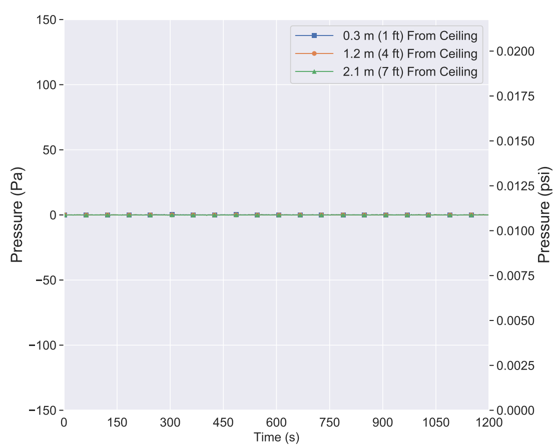
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.60: Experiment 7, no exterior ventilation openings, pressures versus time in all rooms.

Experiment 9

As in Experiment 7, the fire was ignited with an electric match in a plastic waste container located between the bed and the nightstand. The fire grew on and above the corner of the bed near the area of origin. Within one minute of ignition, smoke from the bedroom had spread into the living room. During the next 30 s, flames in the bedding on the right side helped spread fire down the entire length of the bed.

Two minutes after ignition, flames had spread across the top of bed. The smoke layer in the living room and kitchen had formed to a depth of 0.9 m (2.9 ft) below the ceiling. One minute later, about one third of the top surface of the bed appeared to be on fire, and the carpeting between the bed and the front wall of the structure was burning. The hot gas layer continued to grow and smoke was pushing out of the gaps around the exterior vents. The fire continued to grow in bedroom 1 with significant burning near the floor. The hot gas layer increased in depth throughout the structure and the amount of smoke exiting through the gaps around the exterior vents increased.

Flashover had occurred in bedroom 1 approximately 3 min after ignition. Full room fire involvement continued for more than a minute before the fire appeared to decrease in size and the room started to darken down. Black smoke was steadily exhausting through the bottom gap of the front door at this point in time.

Five minutes after ignition, flames were still visible in bedroom 1, although the gas flowing into the hallway appeared to decrease in speed and temperature based on the thermal images.

During the next two minutes the flow of smoke exiting the structure through gaps around the front door and window shutters began to oscillate or pulse, until the flow of smoke out of the structure stopped at 7 min after ignition.

Fifteen minutes after ignition, the firefighters began to ventilate. No flames were evident in the structure at this time. Several minutes later, the firefighters entered the structure and extinguished hot spots on the floor of bedroom 1. Table 4.12 provides details on the fire development.

Table 4.12: Timeline for Experiment 9, Bedroom 1 Fire with all Exterior Vents Closed

Time (s)	Event
0	Ignition in plastic waste container next to bed
60	Flames on and above the corner of bed near the area of origin, smoke flowing from bedroom into living room
90	Flames spread down the length of the right side of bed
120	Flames spreading across the top of the bed, HGL developing in living room and kitchen 0.9 m deep
180	One third of the mattress appears to be burning, flames are spreading on the carpet between the bed and the front wall, HGL continues to grow, smoke exiting out of all exterior vent gaps
210	Fire growing in bedroom 1, significant burning on floor, HGL increased in depth throughout structure Increased smoke flowing from gaps of all exterior openings
240	Only flames are visible in bedroom 1, small flame visible on the exterior of the top of front bedroom window
255	Fire appears to be decreasing, darkening down, black smoke is exhausting through the bottom gap of the front door
300	Flames still visible on bedroom 1 floor, gas exiting bedroom 1 into the hall has decreased in temperature, smoke exiting the structure has started to decrease.
345	Smoke flow exiting the structure has stopped
355	Smoke flow exiting the structure has started pulsing from the structure
420	Pulsing smoke flow has stopped
690	Small flame on the exterior of the right front window shutter
800	Small exterior flame was extinguished
900	Firefighters begin ventilation of structure, no flames are evident in the structure
1125	Firefighters enter structure and extinguish hot spots on the floor of bedroom 1

Figure 4.61 shows the temperatures versus time from the thermocouple array in bedroom 1. The temperatures show the development of the hot gas layer for the first 180 s after ignition, followed by the transition through flashover and temperatures from the ceiling down to the floor in excess of 600 °C (1112 °F). The peak temperatures were approximately 750 °C (1382 °F) at 220 s after ignition. Over the next two minutes the temperatures had decreased to approximately 600 °C (1112 °F). Then the temperatures in the bedroom began to stratify as they continued to decrease. This process continued after the ventilation of the structure started at 900 s after ignition. Note: The sharp momentary drop in the temperatures that occurred between 600 and 1000 s after ignition are artifacts of the data acquisition system and are not representative of temperature pulses.

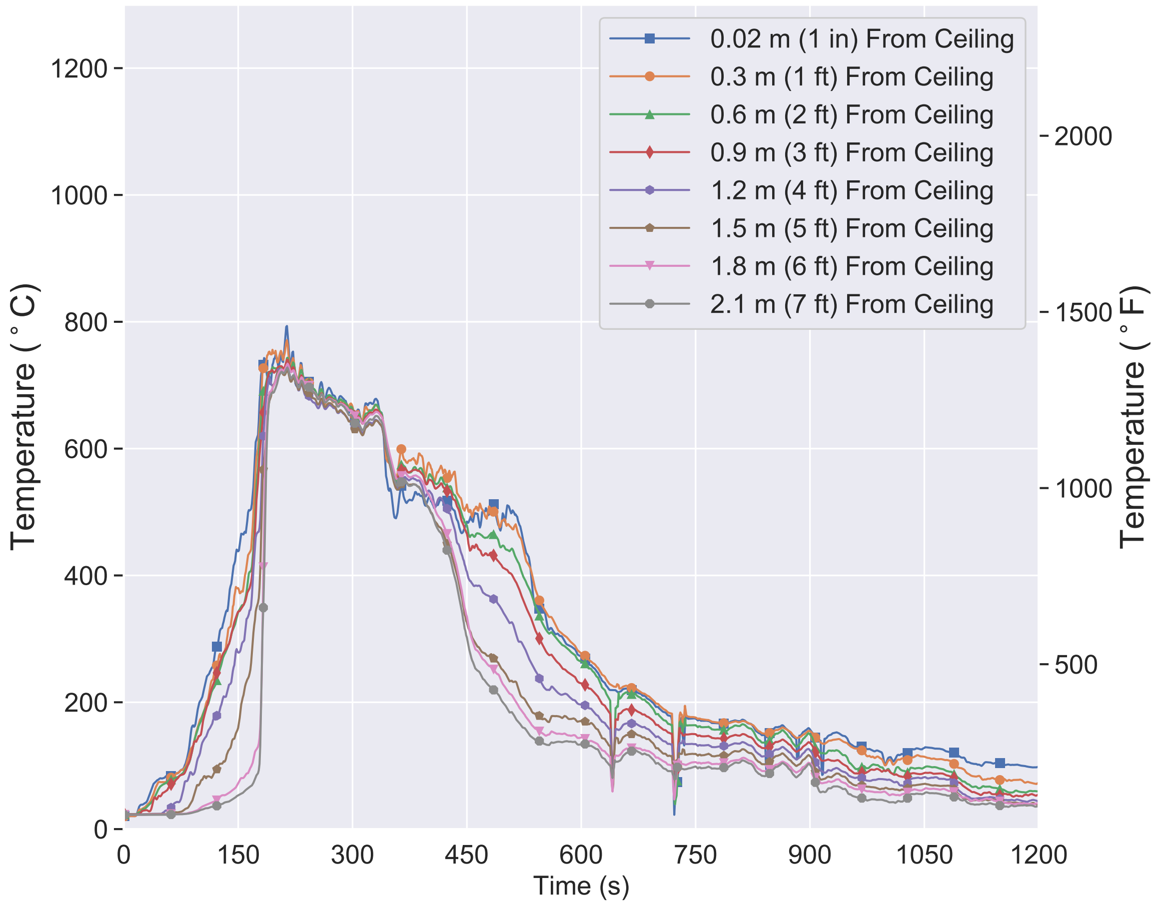
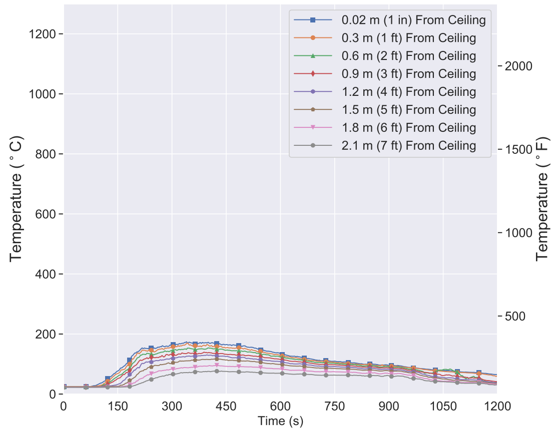
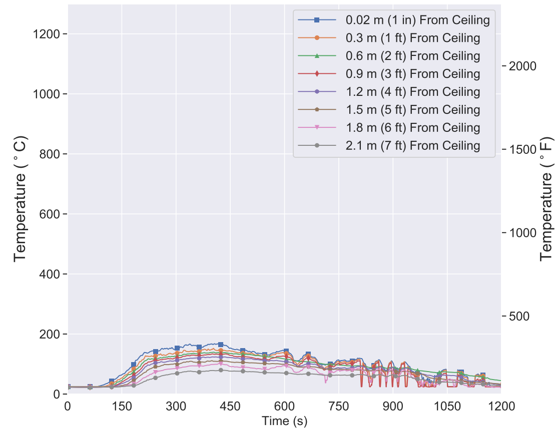


Figure 4.61: Experiment 9, no exterior ventilation openings, bedroom 1 temperatures versus time.

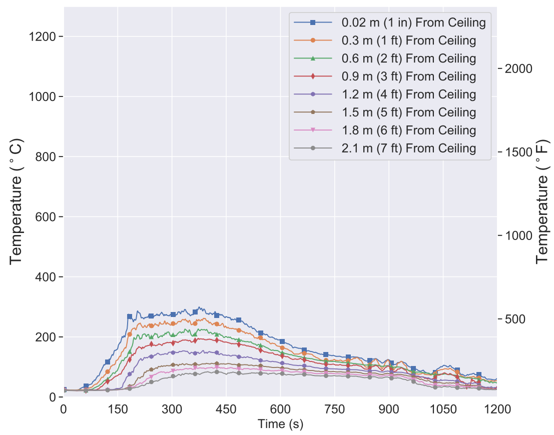
The temperature data from the other thermocouple arrays in the structure appear in Figure 4.62. Again, the thermocouple array (see Figure 4.62c) located closest to bedroom 1 had the highest temperatures, and the temperatures decreased as the distance from bedroom 1 increased. Based on the temperatures, the flames from bedroom 1 did not extend down the hallway to the thermocouple array location. Bedroom 3 was closed, which resulted in a negligible increase in temperature.



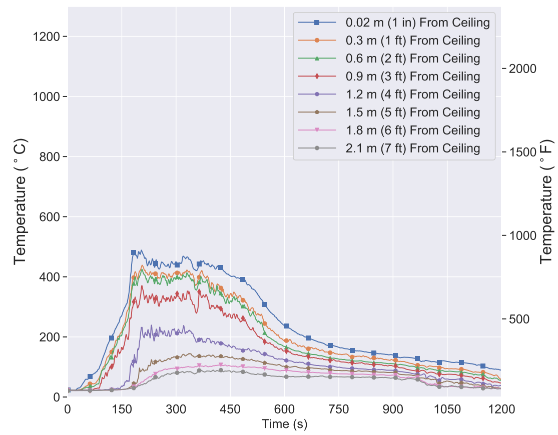
(a) Dining Room Temperature



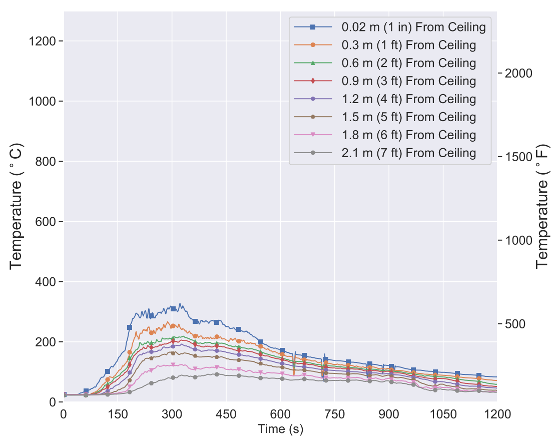
(b) Kitchen Temperature



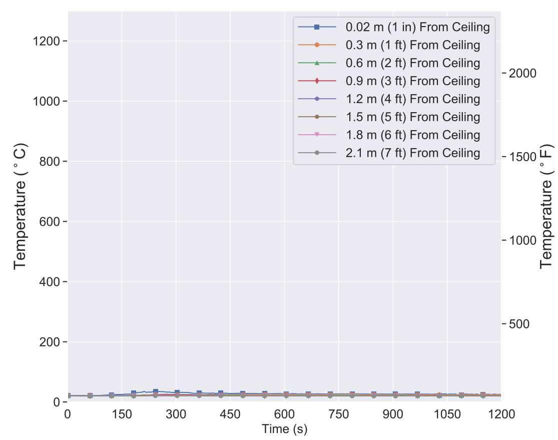
(c) Living Room Temperature



(d) Hallway Temperature



(e) Bedroom 2 Temperature



(f) Bedroom 3 Temperature

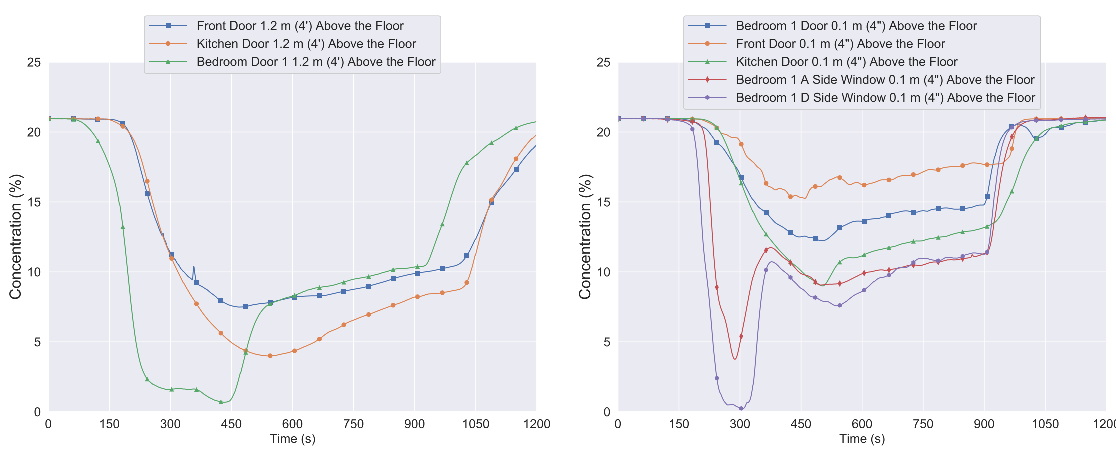
Figure 4.62: Experiment 9, no exterior ventilation openings, temperature time histories for all rooms.

The oxygen sampling locations are the same as described in Experiment 7. In Figure 4.63, the upper graph has three 1.2 m (4 ft) above the floor positions, and the lower graph has the five 0.1 m (4 in.) above the floor positions. The trends are also similar to those measured in Experiment 7.

At 1.2 m (4 ft) above the floor, the oxygen concentration inside the bedroom decreased to below 5% during the period of peak temperatures and then continued to decrease until combustion in the bedroom stopped. The oxygen concentrations at the other two locations decreased below 15% while the temperatures in the bedroom had began to decrease. The timing is in sync with the observation that the fire size had also decreased.

The oxygen probes located at 0.1 m (4 in) above the floor and under the bedroom windows both decreased to oxygen concentrations below 5%. However, the probe located under the head of the bed and closest to the point of ignition (bedroom 1, D side window) decreased at a faster rate, and the oxygen concentration at the location approached 0%. As the flames spread to the carpeting between the bed and the A side (front) wall, the oxygen concentration sampled by the adjacent window began to decrease. As burning near the floor, stopped the oxygen concentrations began to increase.

The lower oxygen probe near the open bedroom door remained above 20% while the fire in the bedroom was growing and oxygen from the rest of the structure was drawn toward the fire room. The smoke pushed into the adjoining open areas of the structure, which caused the oxygen concentration near floor level to decrease at the locations remote from the fire room. The oxygen concentration near the floor at the doorway to the kitchen decreased below 15% at 320 s after ignition. The oxygen concentration level near the floor inside the bedroom doorway decreased below 15% seconds later and remained there until after ventilation was started. The oxygen concentration close to the floor near the front door decreased to almost 15% before starting to increase. In this experiment it would seem the fire self-extinguished due to a lack of oxygen needed for flaming combustion.



(a) Oxygen at 1.2 m Above Floor

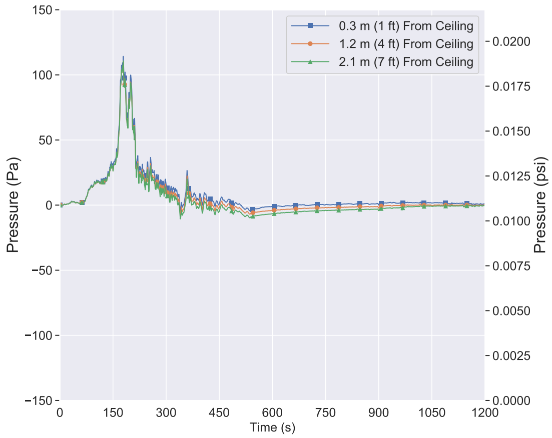
(b) Oxygen at 0.1 m Above Floor

Figure 4.63: Experiment 9, no exterior ventilation openings, oxygen concentration versus time at 1.2 m (top) and 0.1 m (bottom) above the floor.

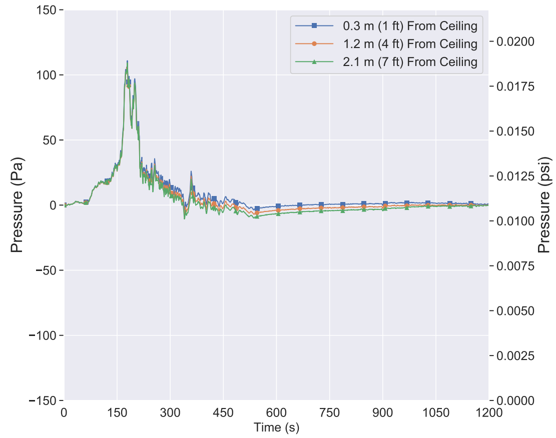
The hallway velocity array measured the gas circulation into and out of bedroom 1 (Figure 4.64). The gases flowing away from the bedroom show a positive velocity, and gases flowing toward the bedroom show a negative velocity. When the fire was near its peak burning rate, more than the top half of the doorway had gases exhausting into the hallway at velocities of about 2 m/s (4.4 mph). At the same time, denser, cooler, gases were flowing into the bottom of the doorway at about 1.5 m/s (3.3 mph). As the energy generated by the fire decreased, the exhaust gases began to slow, and they only flowed out from the upper third of the hallway. The rest of the hallway cross-section served as an supply of cooler gases to the bedroom. It would appear, based on the hallway velocities, the oxygen concentrations and the rate of temperature decrease, that most of the flaming combustion had stopped around 6 min after ignition.

Figure 4.64: Experiment 9, no exterior ventilation openings, hallway velocity versus time. Positive velocity flowing from bedroom to living room.

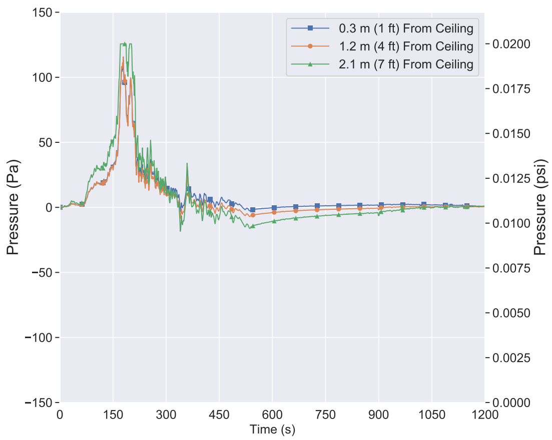
Once again, the pressures throughout the open compartments inside the structure were similar. The pressure data shown in Figure 4.65 increased while the fire in bedroom 1 was growing, and then decreased when the fire started to decay. The pressure fluctuations behind the observations of pulsing smoke exiting the structure appear between 300 and 450 seconds after ignition. It appears the pressures near the ceiling were slightly higher than the pressures near the floor, which would account for the convective circulation in and out of bedroom 1. Bedroom 3, which was closed off from the rest of the structure, did not have a noticeable change in pressure.



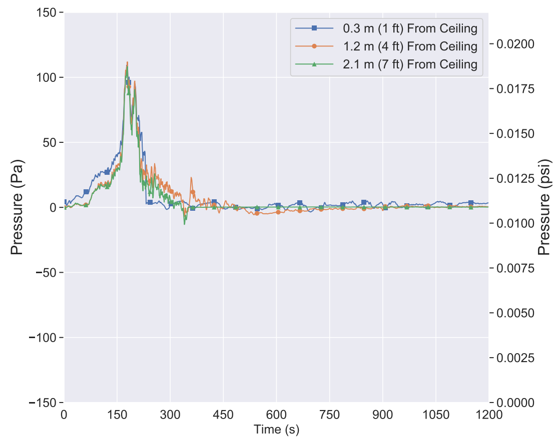
(a) Dining Room Pressure



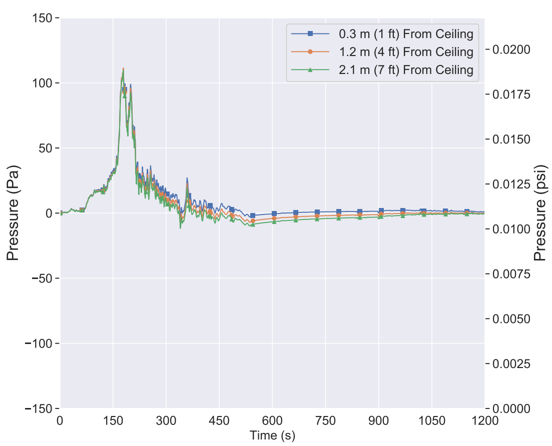
(b) Kitchen Pressure



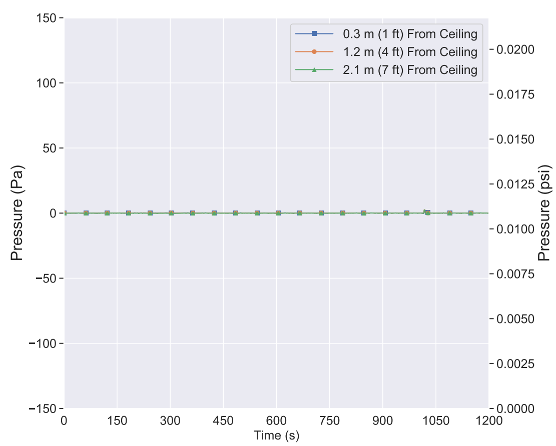
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.65: Experiment 9, no exterior ventilation openings, pressures versus time in all rooms.

4.3.2 Front Door and Bedroom 1 Windows Open

Experiment 12

The fire was ignited in the plastic waste container next to the bed with an electric match. The fire grew on and above the bed near the origin, and 45 s after ignition, light gray smoke began to flow out of the front door. At 90 s post-ignition, flames less than 0.5 m (1.6 ft) extended out of the side D window of bedroom 1. Within two minutes after ignition, the bed was approximately 50% involved, flames extended out of both bedroom windows, and there was black smoke flowing out of the top quarter of the front door. During the next 50 s, the bedroom had transitioned to flashover, flames filled the top half of both windows, flames extended down the hallway, and black smoke flowed out of the top half of the front door. At three minutes after ignition, the fire started to decay as oxygen started to deplete, but, flows from the bedroom windows and front door remained unchanged. At four minutes post-ignition, there was an increase in hallway temperatures as the hallway carpet caught fire. There were minimal noticeable exterior visual changes until five and 30 s after ignition when fire suppression was initiated through the bedroom 1 window. After the bedroom 1 fire suppression, the sofa in the living room began burning on the end closest to the hallway, which required firefighters to enter the structure and extinguish the sofa and hot spots in bedroom 1, 7 min after ignition. Table 4.13 provides a timeline of events for Experiment 12.

Table 4.13: Timeline for Experiment 12, Bedroom 1 Fire with Front Door and Bedroom 1 Windows Open

Time (s)	Event
0	Ignition in plastic waste container next to bed
30	Flames on and above the corner of bed near the area of origin, light gray smoke flowing from both bedroom 1 window openings and into hall
45	Light gray smoke beginning to exit the front door opening
60	Flames spread down the length of the right side of bed
90	Flames less than 0.5 m long extend out of the top of the side D bedroom 1 window opening
120	Fire involves at least half of the bed, carpet next to the right side of the bed is burning, flames extending out of the top of both bedroom 1 windows, black smoke flowing out of the upper quarter of the front door opening, HGL depth is approximately 0.9 m in throughout the open portions of the structure
135	Fire size has increased in bedroom 1 and is beginning the transition to flashover, flames filled the upper half of both bedroom 1 windows, flames extended into the hall, black smoke flowing out of the upper half of the front door opening
170	Only flames are visible in bedroom 1, flames have extended into the hall and the living room, smoke exiting out of all exterior vent gaps
180	Fire in bedroom 1 decreasing, flows from the bedroom windows and the front door seem unchanged
190	Flames are no longer entering the hall from the upper portion of bedroom 1 doorway
240	Carpet in hallway is on fire, flames and smoke flow from bedroom 1 windows and the front doorway have not changed
330	Fire suppression with small hose stream into bedroom 1 window
390	Majority of the fire in bedroom 1 extinguished
395	After bedroom 1 fire suppression, the sofa in the living room began burning on the end closest to the hallway
420	Firefighters enter structure, extinguish the sofa and hot spots in bedroom 1

Figure 4.66 shows the temperatures versus time from the thermocouple array in bedroom 1. The temperatures show the development of the hot gas layer for the first 120 s after ignition, followed by the transition through flashover and temperatures from the ceiling down to the floor in excess of 600 °C (1112 °F). The peak temperatures were in excess of 1000 °C (1832 °F) prior to suppression at 330 s after ignition. It is important to recognize that between 180 s to 330 s after ignition, the temperatures were at or near the upper limit of physical wire, therefore there is increased uncertainty in the measurements. Temperatures decreased after the initial suppression actions, 330 s after ignition.

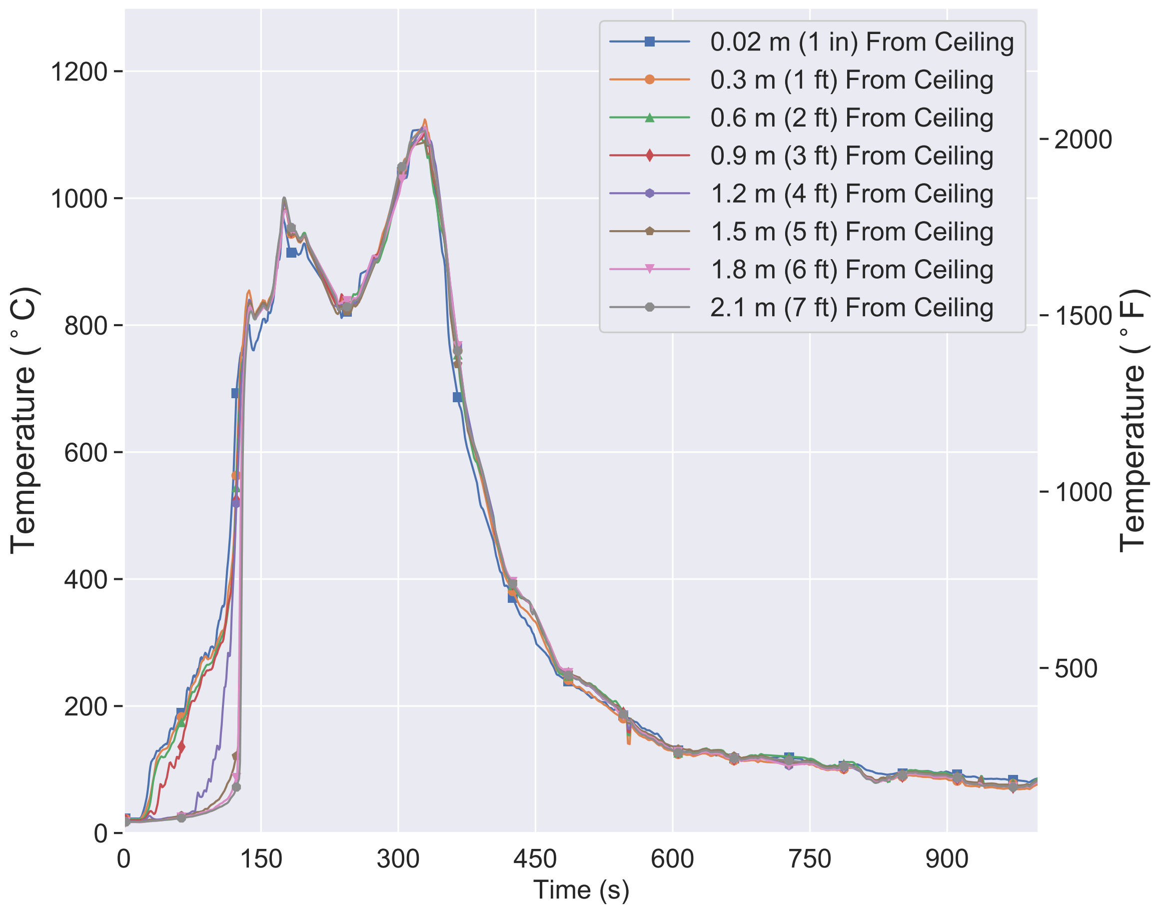
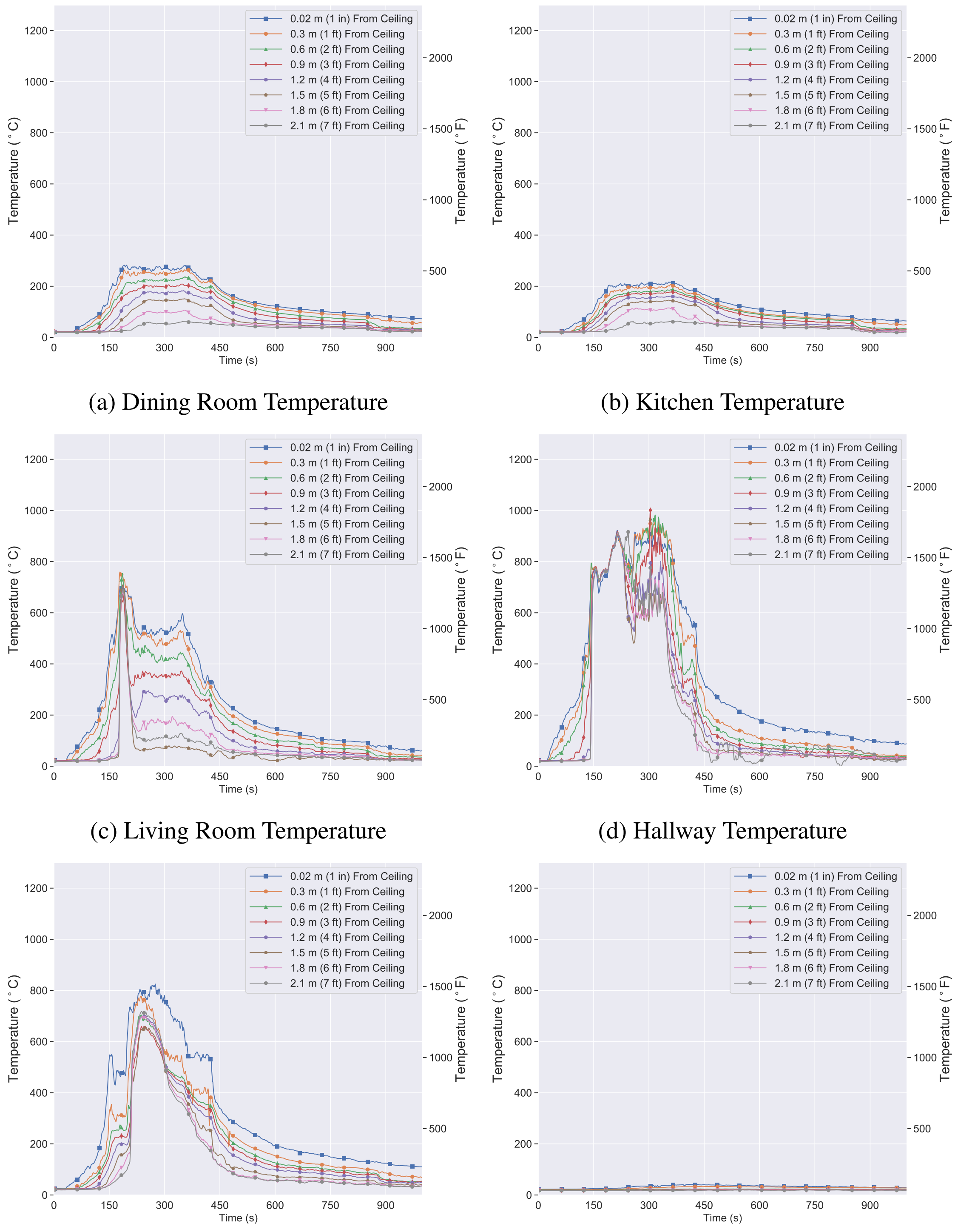


Figure 4.66: Experiment 12, front door and bedroom 1 windows open, bedroom 1 temperatures versus time

The temperature data from the other thermocouple arrays in the structure are presented in Figure 4.67. The hallway (see Figure 4.67c) and living room (see Figure 4.67b) thermocouple arrays were located in the flow path between bedroom 1 and the front door, and therefore had the highest temperatures of the open adjacent spaces. The hallway area temperatures exceeded 600 °C (1112 °F) from floor to ceiling approximately 150 s after ignition and remained at that level until the temperatures re-stratified 90 s later, an indication of flashover. At approximately 180 s after ignition, the living room temperature rapidly grew to have floor to ceiling temperatures in excess of 600 °C (1112 °F) for about 5 s before rapidly decreaseing and stratifying. This corresponds with the video evidence of flames traveling down the hallway toward the front door. As the distance between the fire room and the thermocouple array increased, the peak temperatures decreased. Bedroom 2 also saw a significant rise in temperature due to its open door's proximity to bedroom 1, but not as severe as the hallway because of the lack of oxygen flow to the room. Bedroom 3 was closed, which resulted in a negligible increase in temperature.



(a) Dining Room Temperature

(b) Kitchen Temperature

(c) Living Room Temperature

(d) Hallway Temperature

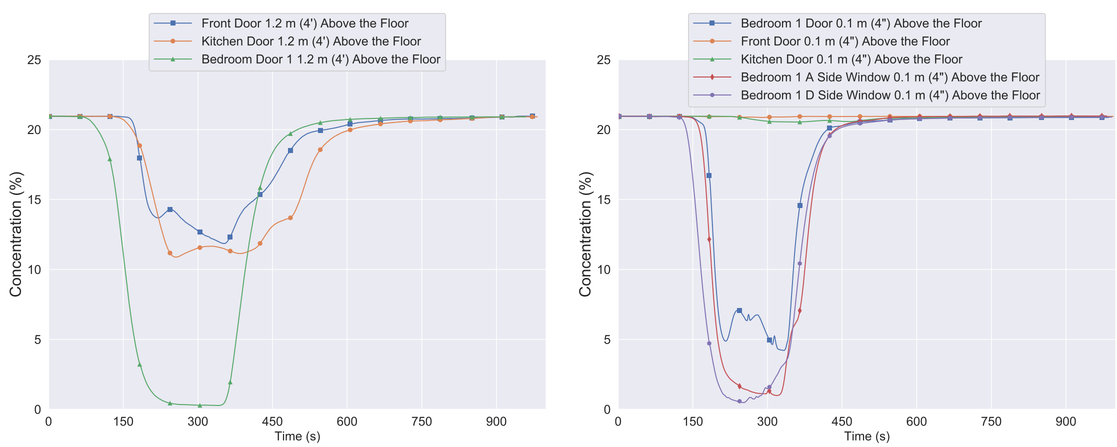
(e) Bedroom 2 Temperature

(f) Bedroom 3 Temperature

Figure 4.67: Experiment 12, front door and bedroom 1 windows open, temperature time histories for all rooms.

Figure 4.68 shows the oxygen concentrations at different locations in the structure at two different elevations, 1.2 m (4 ft) above the floor and 0.1 m (4 in) above the floor. The top graph has three 1.2 m (4 ft) positions, one located just inside the bedroom 1 doorway, another in the doorway from the living room to the kitchen, and one adjacent to the closed front door. The oxygen level inside the bedroom decreased to near zero at about the time of peak temperatures. The oxygen concentrations at the other two locations decreased below 15% just as the temperatures in the bedroom had begun to decrease, which correlated with the observation that the fire size had also decreased.

In addition to three locations listed for the 1.2 m (4 ft) positions, five additional sample probes were added at the 0.1 m (4 in) above the floor level. Three oxygen sample probes were located in bedroom 1, one below each window and one at the doorway. The two probes near the floor below the windows in bedroom 1 exhibited the lowest oxygen concentrations, dropping below 1%. The lower oxygen probe near the open bedroom door remained slightly higher, dropping to 5% while the fire in the bedroom was growing, and oxygen from the rest of the structure was drawn toward the fire room. As smoke was pushed into the adjoining open areas of the structure, the oxygen concentration in the room decreased more than the bedroom doorway location. The oxygen levels in the kitchen and front door stayed above 20%, indicating the smoke layer did not descend below the 0.1 m (4 in) level in remote rooms within the structure.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.68: Experiment 12, front door and bedroom 1 windows open, oxygen concentration versus time at 1.2 m (top) and 0.1 m (bottom) above the floor.

The velocity profile at the front door (see Figure 4.69) confirms the visual observations that the top portion of the doorway was primarily exhaust. The smoke layer did not descend beyond the hallway mark of the doorway as the velocity profile remained an intake from 120 s after ignition until suppression.

Figure 4.69: Experiment 12, front door and bedroom 1 windows open, front door velocity versus time.

The velocity array in the hallway measured the gas flow circulation into and out of bedroom 1. Figure 4.70 shows the gases flowing out of the bedroom with a positive velocity and gases flowing into the bedroom with a negative velocity. When the fire was near its peak burning rate, more than the top half of the doorway had gases exhausting into the hallway at velocities of about 2.5 m/s (5.6 mph). At the same time, denser, cooler gases were flowing into the bottom of the doorway at a peak of about 4.5 m/s (9 mph). After fire suppression, the fire decreased in size and exhaust gases slowed. The short period of time when the entrainment was overcome coincides with the ignition of the hallway carpet.

The open windows in the fire room had similar velocity profiles, as shown in Figure 4.71. The top half of each window was in exhaust with upper probe velocities greater than 9 m/s (20 mph) and middle window velocities of approximately 4.4 m/s (9.8 mph). The bottom probe was the only probe that was an inlet, peaking around 2.3 m/s (5 mph). The probe labeled “middle bottom” in Figure 4.71 was the inflection point that fluctuated between being in inlet or outlet.

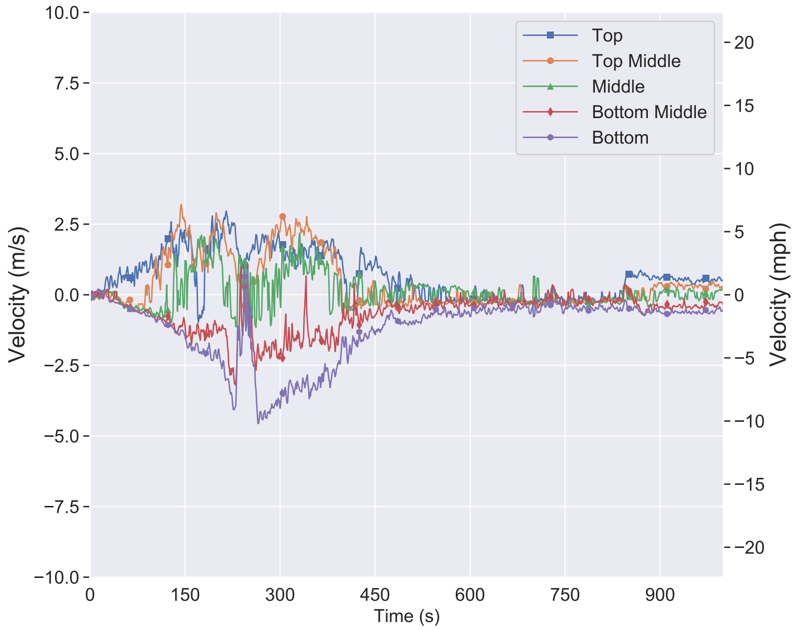
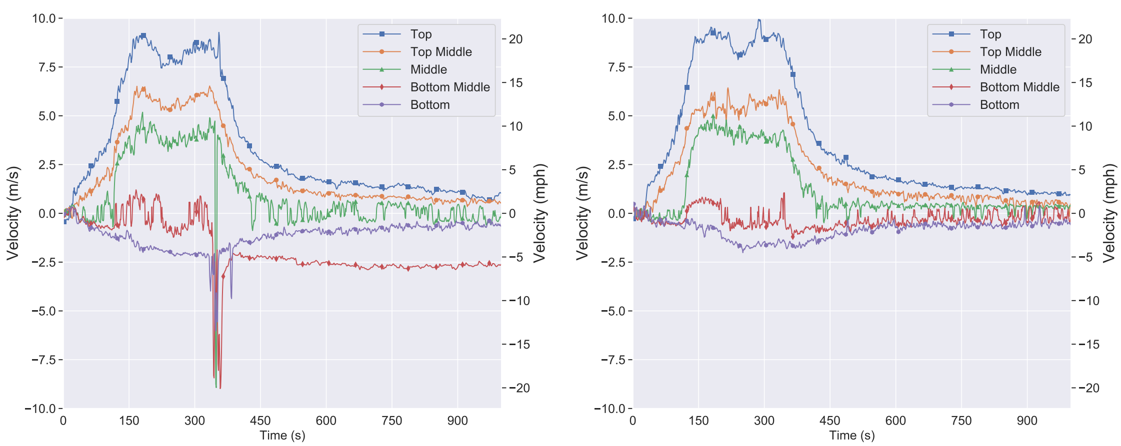


Figure 4.70: Experiment 12, Front door and bedroom 1 windows open, hallway velocity versus time. Positive pressure flowing from bedroom to living room.

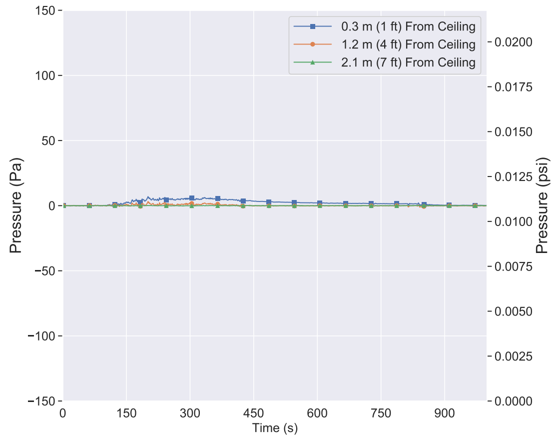


(a) Bedroom 1 Side A Window

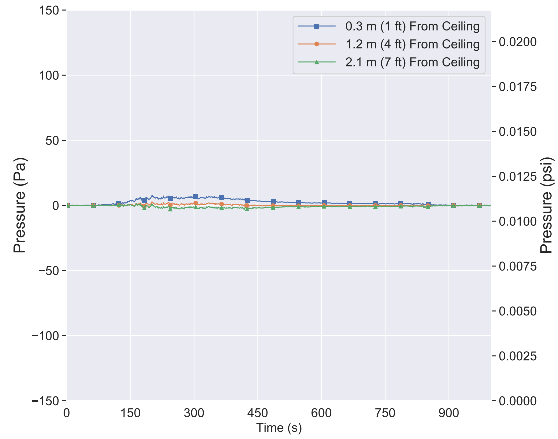
(b) Bedroom 1 Side D Window

Figure 4.71: Experiment 12, front door and bedroom 1 windows open, bedroom 1 windows, velocity versus time. Positive velocity is flow leaving the structure.

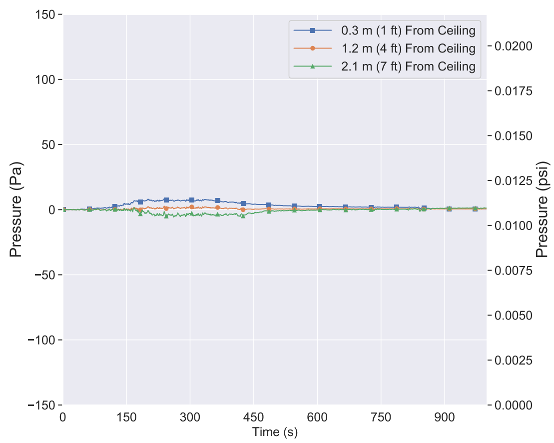
Pressures inside the structure at locations open to the fire room were similar, as shown in Figure 4.72. Pressures near the ceiling were slightly higher than the pressures near the floor, which accounts for the convective circulation in and out of bedroom 1. Bedroom 3 was closed off from the rest of the structure and did not have a noticeable change in pressure.



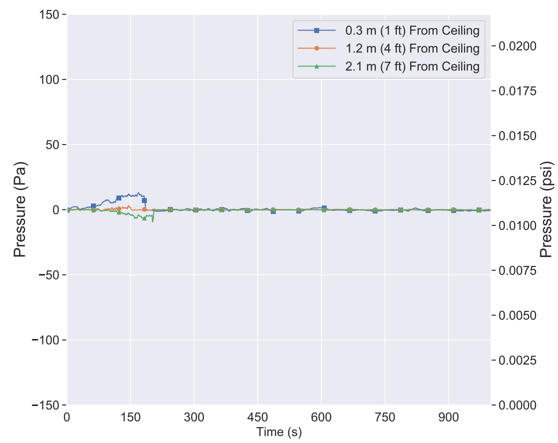
(a) Dining Room Pressure



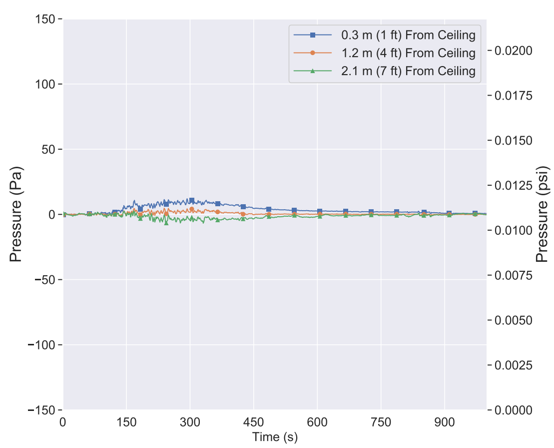
(b) Kitchen Pressure



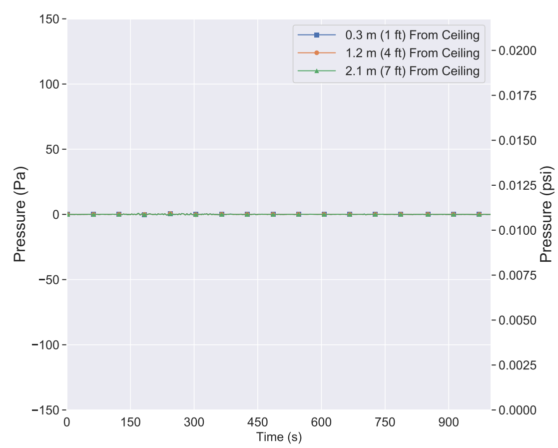
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.72: Experiment 12, front door and bedroom 1 windows open, pressures versus time in all rooms.

Experiment 13

The fire was ignited in the plastic waste container next to the bed with an electric match. The fire grew and spread to the front edge of the bed 30 s after ignition. Light gray smoke was visible out of the bedroom windows and in the hallway. One minute after ignition, there was light gray smoke at the front door as fire spread along the bed. Within two minutes after ignition, a hot gas layer had developed into the living room and kitchen that was 0.6 m (2 ft) thick. Thirty seconds later, flames had extended across the head of the bed to the night stand and were visible outside of the side D window. Between 170 s to 190 s after ignition, flames were visible from both windows, flames extended into the hallway, and there was black smoke flowing out the top half of the front door as the room transitioned to flashover.

Three and half minutes post-ignition, bedroom 1 appeared to be burning floor to ceiling, but only in the portion of the room where the bed was located. The hot gas layer was approximately 0.9 m thick in the living room and 1.2 m in the kitchen. At four minutes after ignition, the fire in bedroom appeared to start to decay, but flows from bedroom windows and front door remainedunchanged. Burning in the hallway near the floor continued through 5 min post-ignition and the hot gas layer in the living room dropped to 2.1 m below the ceiling and 1.8 m in the kitchen. The sofa at the end of the hallway was off-gassing and ignited 1 min later. Visible conditions at the vents remained steady until the initial suppression through the bedroom 1 window occurred 7 min and 30 s after ignition. Table 4.14 provides a timeline of events for Experiment 13.

Table 4.14: Timeline for Experiment 13, Bedroom 1 Fire with Front Door and Bedroom 1 Windows Open

Time (s)	Event
0	Ignition in plastic waste container next to bed
30	Flames spread to front edge of bed, light gray smoke flowing from both bedroom 1 window openings and into hall
60	Fire growing, flames on and above the corner of bed near the area of origin, light gray smoke beginning to exit the front door opening
120	Fire still burning on the corner of the bed near the area of origin, HGL in living room and kitchen 0.6 m thick
150	Flames spread across the head of the bed and over to the nightstand, flames extended out of the top of the side D bedroom 1 window opening
170	Flames extend out of the front bedroom 1 window opening, black smoke is flowing out of the upper quarter of the front door opening
190	Fire size has increased in bedroom 1, the transition to flashover has begun, flames filled the upper half of both bedroom 1 windows, flames extended into the hall, black smoke flowing out of the upper half of the front door opening
200	Top surface of bed is on fire
210	Bedroom 1 appears to be burning floor to ceiling but only in the portion of the room where the bed is located, area between the foot of the bed and the side B wall is free of fire near the floor, HGL is approximately 0.9 m thick in the living room and 1.2 m in the kitchen
240	Fire in bedroom 1 appears to be decreasing, flows from the bedroom windows and the front door seem unchanged
250	Flames entering the hall are decreasing in size, the flames and smoke exiting the bedroom 1 windows and the front door have not changed
300	Burning in the hallway near the floor continues, HGL in the living room is 2.1 m below the ceiling and 1.8 m in the kitchen
360	Burning low near the floor continues in bedroom 1 and in the hallway, the end of the sofa near the hall is off gassing and maybe on fire
450	Fire conditions have remained steady, fire suppression begina with small hose stream into bedroom 1 window
510	Majority of the fire in bedroom 1 has been extinguished
540	Firefighters enter structure, extinguish the sofa and hot spots in bedroom 1

Figure 4.73 shows the temperatures versus time from the thermocouple array in bedroom 1. The temperatures show the development of the hot gas layer during the first 180 s after ignition, followed by the transition through flashover and temperatures from the ceiling down to the floor in excess of 600 °C (1112 °F). The peak temperatures were in excess of 1000 °C (1832 °F) prior to suppression at 420 s after ignition. Temperatures decreased after the initial suppression actions, 450 s after ignition.

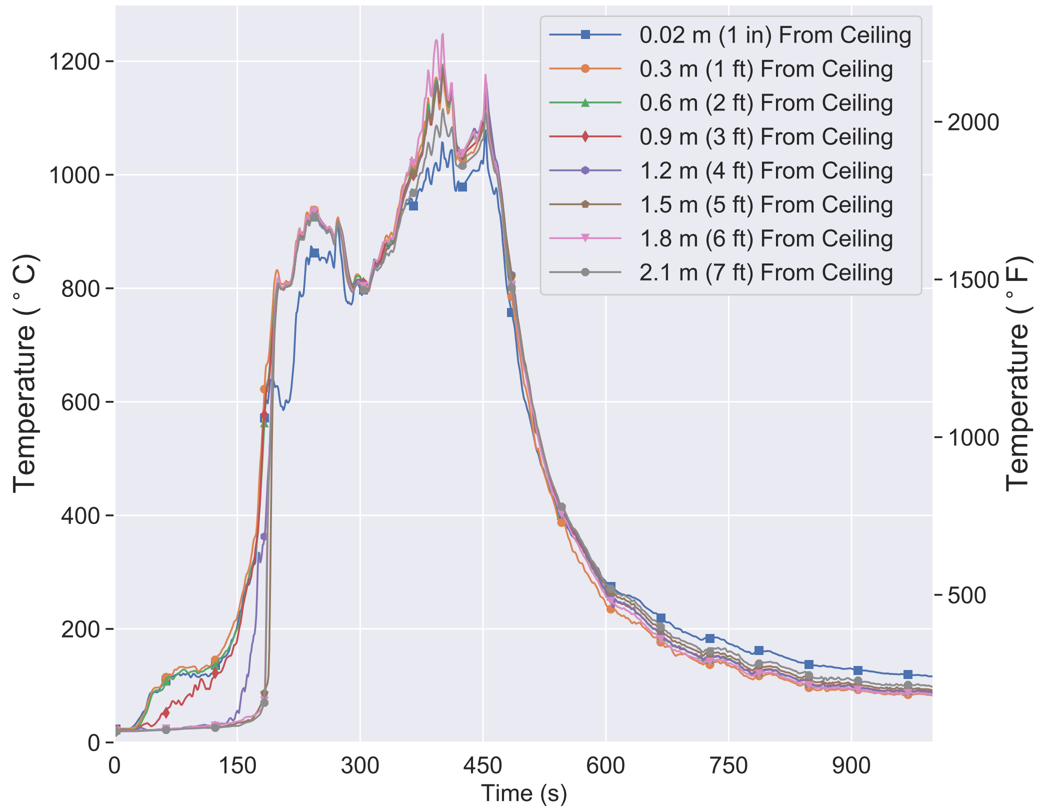
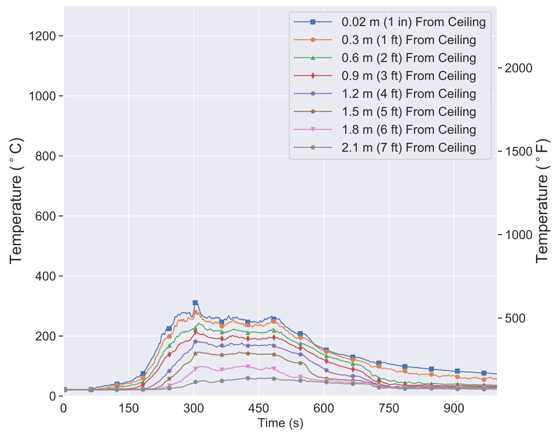
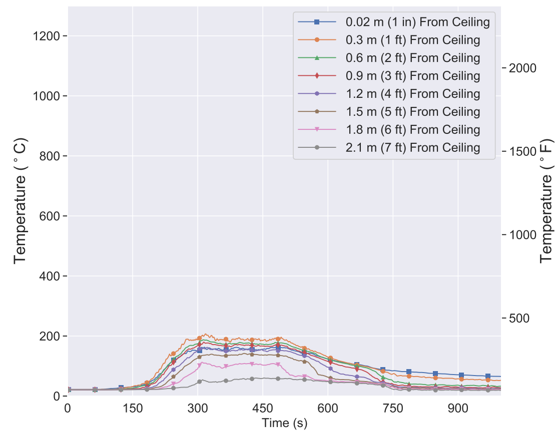


Figure 4.73: Experiment 13, front door and bedroom 1 windows open, bedroom 1 temperatures versus time.

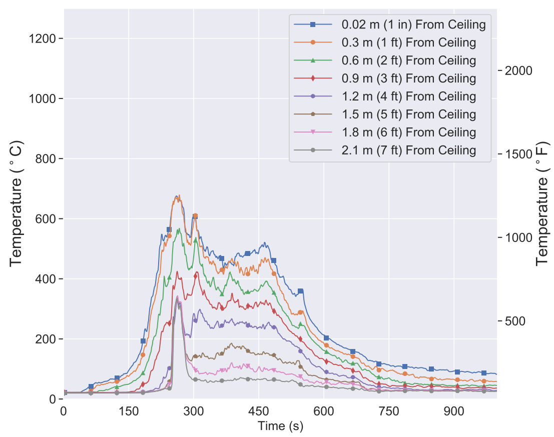
The temperature data from the other thermocouple arrays in the structure are appear in Figure 4.74. The hallway (see Figure 4.74c) and living room (see Figure 4.74b) thermocouple arrays were located in the flow path between bedroom 1 and the front door, therefore had the highest temperatures of the open adjacent spaces. The hallway area temperatures exceeded 600 °C (1112 °F) from floor to ceiling approximately 200 s after ignition, and remained at that level until suppression. At approximately 250 s after ignition, the living room temperature rapidly grew but temperatures 1.2 m (4 ft) from the ceiling never exceeded 350 °C (662 °F). Bedroom 2 also saw a significant rise in temperature due to its open door's proximity to bedroom 1, but not as severe as the hallway because of the lack of oxygen flow to the room. As the distance between the fire room and the thermocouple array increased, the peak temperatures decreased. Bedroom 3 was closed, which resulted in a negligible increase in temperature.



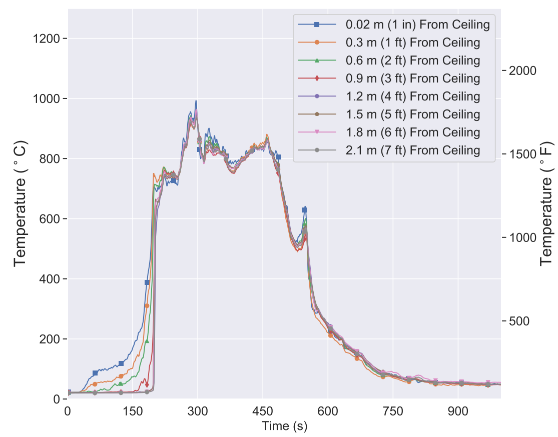
(a) Dining Room Temperature



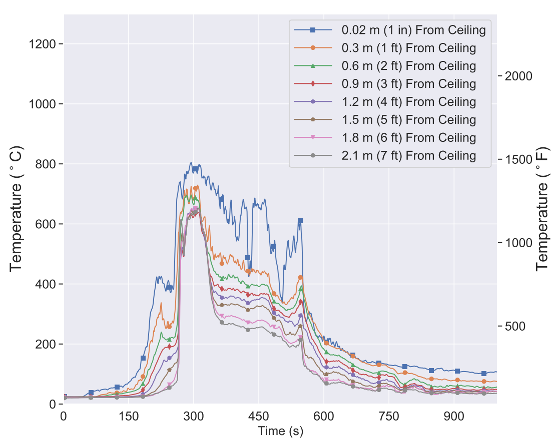
(b) Kitchen Temperature



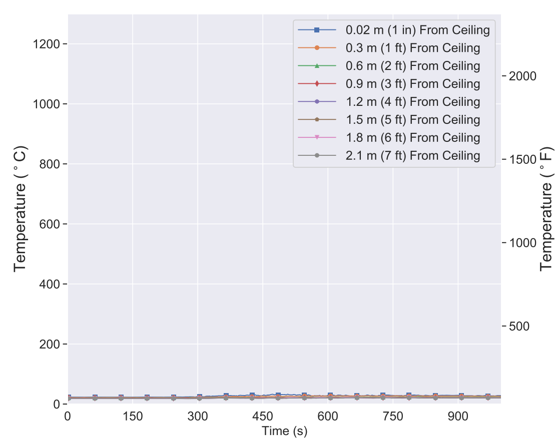
(c) Living Room Temperature



(d) Hallway Temperature



(e) Bedroom 2 Temperature

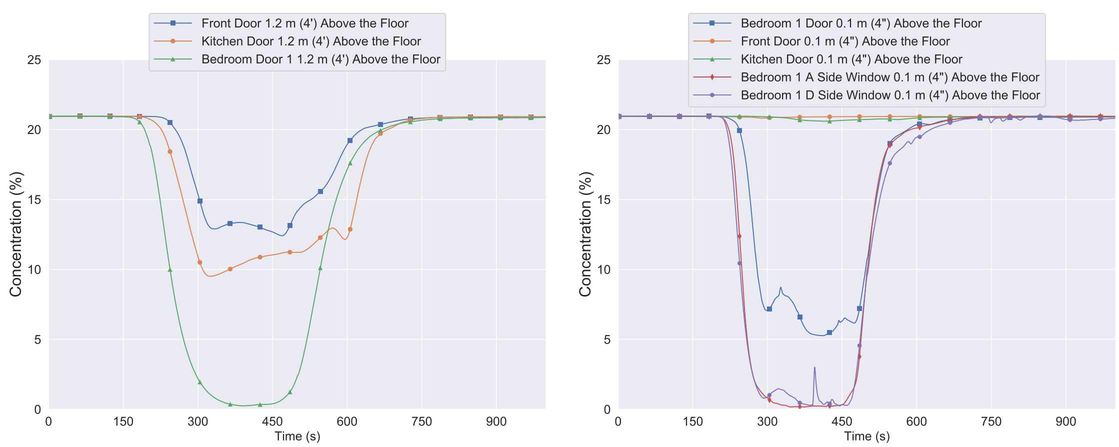


(f) Bedroom 3 Temperature

Figure 4.74: Experiment 13, front door and bedroom 1 windows open, temperature time histories for all rooms.

Figure 4.75 shows the oxygen concentrations at different locations in the structure at two different elevations, 1.2 m (4 ft) above the floor and 0.1 m (4 in) above the floor. The top graph shows three 1.2 m (4 ft) positions, one located just inside the bedroom 1 doorway, another in the doorway from the living room to the kitchen, and one adjacent to the closed front door. The oxygen level inside the bedroom decreased to zero at about the time of peak temperatures. The oxygen concentrations at the other two locations decreased to between 10% to 15% just as the temperatures in the bedroom had begun to decrease, which correlated with the observation that the fire size had also decreased.

In addition to three locations listed for the 1.2 m (4 ft) positions, five additional sample probes were added at the 0.1 m (4 in) above the floor level. Three oxygen sample probes were located in bedroom 1, one below each window and one at the doorway. The two probes near the floor below the windows in bedroom 1 exhibited the lowest oxygen concentrations, dropping to near 0%. The lower oxygen probe near the open bedroom door remained slightly higher, dropping to 5% while the fire in the bedroom was growing and oxygen from the rest of the structure was drawn toward the fire room. As smoke was pushed into the adjoining open areas of the structure, the oxygen concentration in the room decreased more than the bedroom doorway location. The oxygen levels in the kitchen and front door stayed above 20%, indicating the smoke layer did not descend below the 0.1 m (4 in) level in remote rooms within the structure.



(a) Oxygen at 1.2 m Above Floor

(b) Oxygen at 0.1 m Above Floor

Figure 4.75: Experiment 13, front door and bedroom 1 windows open, oxygen concentration versus time at 1.2 m (top) and 0.1 m (bottom) above the floor.

The velocity profile at the front door (Figure 4.76) confirms the visual observations that the top portion of the doorway was primarily exhaust. The smoke layer did not descend below the top half of the doorway because the velocity profile shows the lower half of the doorway served as an air intake from 180 s after ignition until suppression.

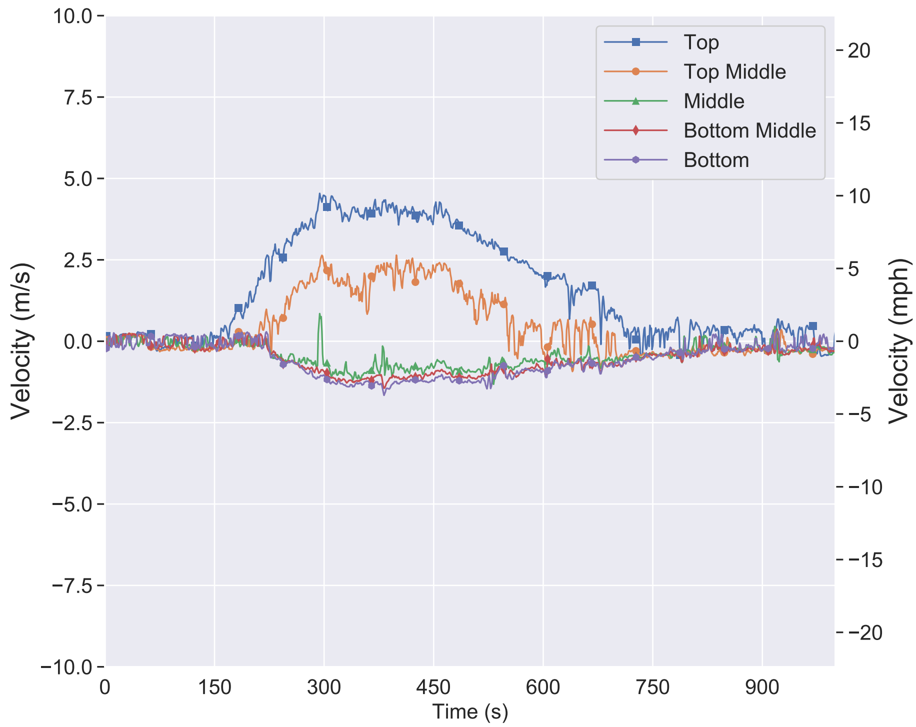


Figure 4.76: Experiment 13, front door and bedroom 1 windows open, front door velocity versus time.

The velocity array in the hallway, shown in Figure 4.77, measured the gas flow into and out of bedroom 1. The gases flowing out of the bedroom show a positive velocity, and gases flowing into the bedroom show a negative velocity. When the fire was near its peak burning rate, more than the top half of the doorway had gases exhausting into the hallway at velocities of about 2.5 m/s (5.6 mph). At the same time, denser, cooler gases were flowing into the bottom of the doorway at a peak of about 4.5 m/s (9 mph). After fire suppression, the fire decreased in size and exhaust gases slowed. The short period of time when the entrainment was overcome coincides with the ignition of the hallway carpet.

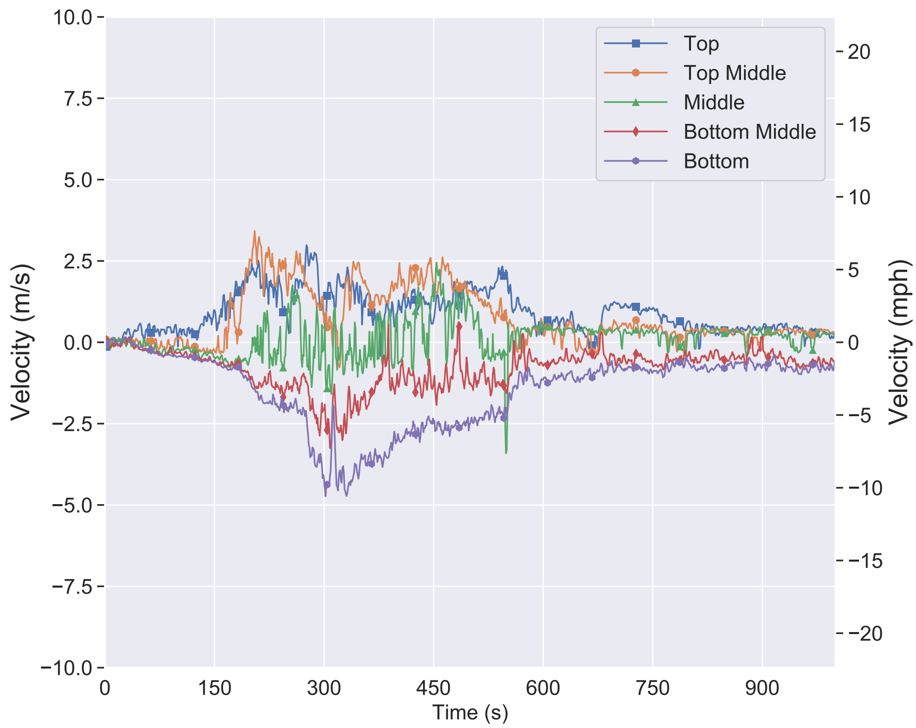
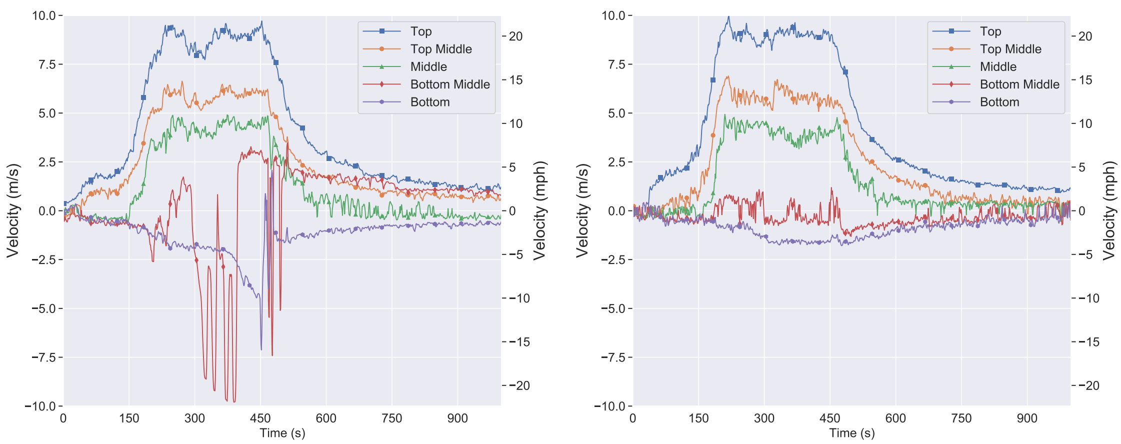


Figure 4.77: Experiment 13, front door and bedroom 1 windows open, hallway velocity versus time.

The open windows in the fire room had similar velocity profiles, as shown in Figure 4.78. The top half of each window was in exhaust with upper probe peak velocities of 10 m/s (22 mph) and middle window velocities of approximately 5 m/s (11 mph). The bottom probe was the only probe that was an inlet, peaking around 2.3 m/s (5 mph). The probe labeled "middle bottom" in Figure 4.78 was the inflection point that fluctuated between being in inlet or outlet. Note that the bottom middle probe on the side A window appeared to stop functioning approximately 180 s after ignition.

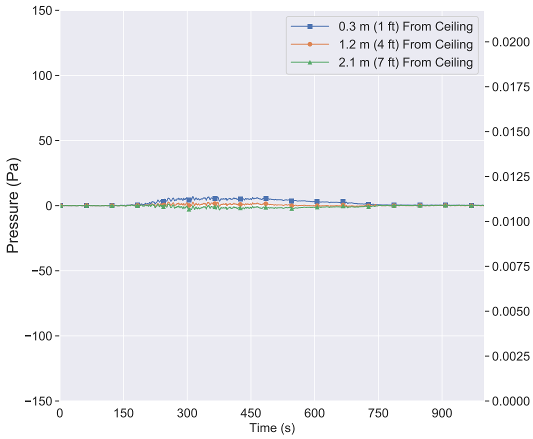


(a) Bedroom 1 Side A Window

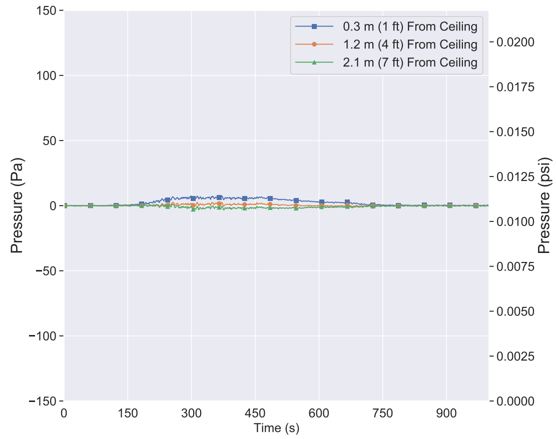
(b) Bedroom 1 Side D Window

Figure 4.78: Experiment 13, front door and bedroom 1 windows open, bedroom 1 windows, velocity versus time. Side A probes are on the left and side D probes are on the right. Positive velocity is flow leaving the structure.

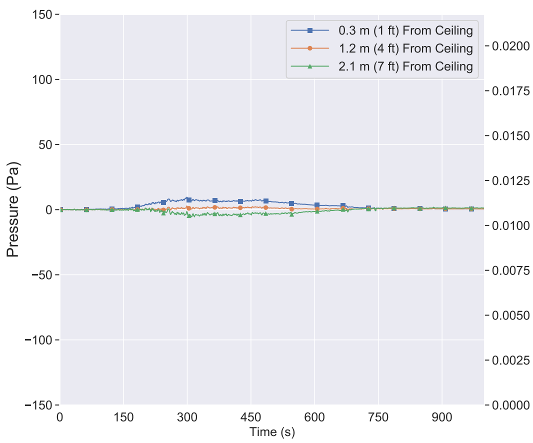
Pressures inside the structure at locations open to the fire room were similar, as shown in Figure 4.79. Pressures near the ceiling were slightly higher than the pressures near the floor, which accounts for the convective circulation in and out of bedroom 1. Bedroom 3, closed off from the rest of the structure, did not have a noticeable change in pressure.



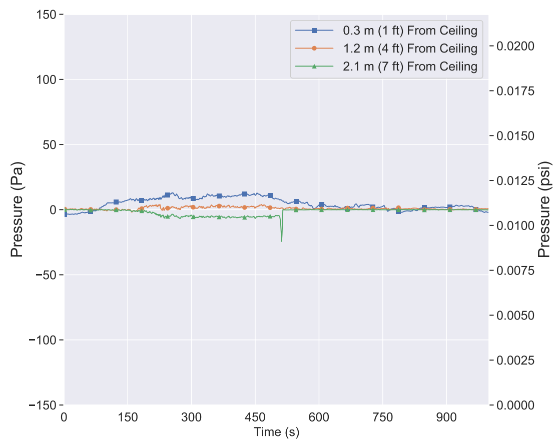
(a) Dining Room Pressure



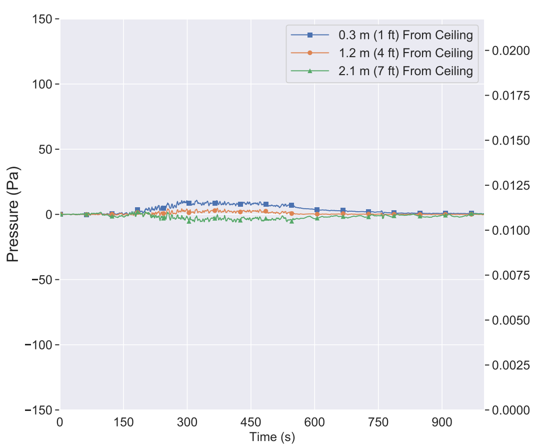
(b) Kitchen Pressure



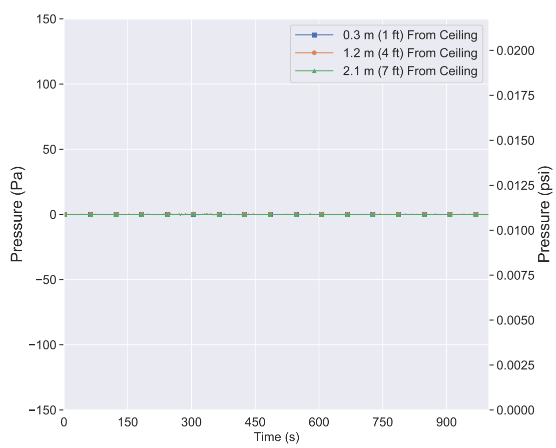
(c) Living Room Pressure



(d) Bedroom 1 Pressure



(e) Bedroom 2 Pressure



(f) Bedroom 3 Pressure

Figure 4.79: Experiment 13, front door and bedroom 1 windows open, pressures versus time in all rooms.

5 Two Story Results

The two-story structure experiments provided an opportunity to examine the impact of ventilation in a larger structure with vents that were more remote and at different elevations from the area of origin. Table 3.2 lists the experiments.

Five experiments were conducted in the family room, and each experiment had a different ventilation arrangement. The family room was the central room on the rear side of the structure. The family room was two stories high and open to the hallway on the second floor.

Experiment 1 was conducted with all of the exterior vents closed. The only means for gases to communicate between the exterior and interior of the structure would be the small gaps around the door and window openings. Keep in mind that at a pressure difference of 10 Pa (0.0014 psi), the two-story structure had an estimated equivalent leakage area of 0.16 m^2 (1.8 ft^2).

The next three family room experiments, Experiments 2–4, had a progression of ventilation changes. Experiment 2 had the front door as the only open vent. Experiment 3 had the front door open, bedroom 3 was open to the upstairs hallway, and the window was open. Experiment 4 had the front door open, bedrooms 2 and 4 were open to the upstairs hallway, and their windows were open to the exterior. The bedroom windows served as the most remote vents.

The last experiment in the family room, Experiment 8, had the front door open as well as an open window in the family room adjacent to the area of origin. This experiment was different from the previous experiments with two vents on the first floor. One of the vents was remote while the other was close to the seat of the fire. In the previous experiments, all of the vents were remote from the area of origin.

The kitchen was located in the far rear corner of the structure. Experiment 5 was conducted with only the front door open and all of the other exterior door and window openings closed for the duration of the experiment. The fire in the kitchen was started in an elevated position on the countertop.

The laundry room was in the front left corner of the structure. For Experiment 6, the only opening to the laundry room was an open doorway that connected to the kitchen via a hallway. The front door of the structure was open for the duration of the experiment. This experiment also had an elevated ignition position on top of the washing machine.

The den was the room of fire origin in Experiment 7. The den window was open to the exterior, and the den doorway was open to the open floor area of the family room and living room. The other opening to the exterior was the front door.

Table 5.1: Experiments in Two-Story Structure

Exp #	Fire Location	Ventilation
1	Family Room	All Vents Closed
2	Family Room	Front Door Open
3	Family Room	Front Door Open, Bedroom 3 Door and Window Open
4	Family Room	Front Door Open, Bedroom 2 and 4 Doors and Windows Open
8	Family Room	Front Door and Family Room Window Open
5	Kitchen	Front Door Open
6	Laundry Room	Front Door Open
7	Den	Front Door and Den Window Open

5.1 Family Room Fires

The family room fires used the same fuel package as the living room fires in the single story structure. The arrangement of the furniture was a mirror image of the layout used in the single story. As a result, the ignition side of the sofa was moved from the left to the right side of the sofa positioned against the wall as shown in Figure 3.21.

5.1.1 All Exterior Vents Closed

Experiment 1

The sofa was ignited (t = 0 s) with a remote operated electric match. As the fire grew on the right side of the sofa, a definitive thermal plume formed. Within 30 s after ignition, the flames had extended above the back of the sofa and began to expose the gypsum wallboard. Within a minute after ignition, visible smoke had reached the ceiling on the upper level and began to spread across the ceiling. The fire continued to grow, and within 3 min after ignition, the flames had extended to approximately 1.2 m (4 ft) above the back of the sofa, and the base of the fire was about 0.6 m (2 ft) square. The hot gas layer had begun to form on the ceiling of the upper level.

The fire on the sofa burned through the back of the sofa near the point of ignition. This allowed the flames to spread along the back so that a second thermal plume was evident on the side of the sofa opposite the point of ignition. The two plumes coexisted for about 30 s prior to merging into one as the full seating area of the sofa became involved in flames. The radiation from the flames on the ignition sofa began to pyrolyze the adjacent sofa. The second sofa had ignited by 4 min and 30 s after ignition. At this point, flames were flowing across the upper level ceiling, and pressure had built up inside the structure as gases were pushed around the closed front door and through gaps around the closed family room window closest to the ignition sofa. The gases pushing out around the family room window auto ignited as they exited the structure.

The area of the family room closest to the ignition sofa was transitioning through flashover at 280 s after ignition. Within seconds, the fire in the family room began to decrease. Smoke stopped pushing out of the structure within 310 s after ignition. By the time firefighters entered the structure, 15 min after ignition, the fire had self extinguished. Table 5.2 provides a timeline of events.

Table 5.2: Timeline for Experiment 1, Family Room Fire with all Exterior Vents Closed

Time (s)	Event
0	Ignition on right side of sofa
30	Flames extend past the top of the back of the sofa, gypsum board exposed to flame
60	Smoke reaches ceiling in family room
120	Flames have extended vertically approximately 0.9 m to 1.2 m above the back of the sofa
180	Fire has a base of approximately 0.6 m on a side, flame height has increased to 2 m, and HGL is forming at second floor ceiling
210	Fire has spread along the back side of the sofa, flames have extended to the side of the sofa opposite the area of origin.
225	Fire still limited to sofa ignited, there are two thermal plumes, one on each end of the sofa
240	The two plumes on the sofa have merged into one, adjacent sofa is pyrolyzing, flames extending approximately 3.5 m above the floor, the HGL has grown to 1.2 m thick on the second floor, abd smoke also appears to be collecting under the first floor ceiling
255	Flames rolling the ceiling over the second floor hallway and light gray smoke exiting through gaps around upper half of front door
270	Second sofa has ignited,vfire has spread to end table, smoked continues to flow around the front door, and smoke is also flowing from gaps in the bedroom 1 window on the backside and the family room window closest to the area of origin
280	Family room transitioning through flashover, HGL is within 0.3 m of the floor, and smoke exiting the family room window is burning on the exterior
300	Fire in family room is decreasing, and smoke exiting around entire perimeter of door, top to bottom
310	Smoke stopped exiting door and window gaps and thermal images indicate cooling on the first and second floor
600	Structure full of smoke and some smoke is flowing out of family room window closest to area of origin
900	Firefighters open family room window shutters, shutters are burning on edges, and shutters are extinguished with no evidence of active burning inside structure
990	Firefighters enter front door of structure, no suppression, no rekindle

Figure 5.1 displays the time history of the temperatures of the thermocouple array positioned in the center of the family room, the closest array to the point of ignition. The graph shows the build up of the hot gas layer from the ceiling down to the floor. Within 300 s after ignition, the temperature neared a peak of 900 °C (1652 °F) followed by a decrease of at least 700 °C (1292 °F) over the next 3 min.

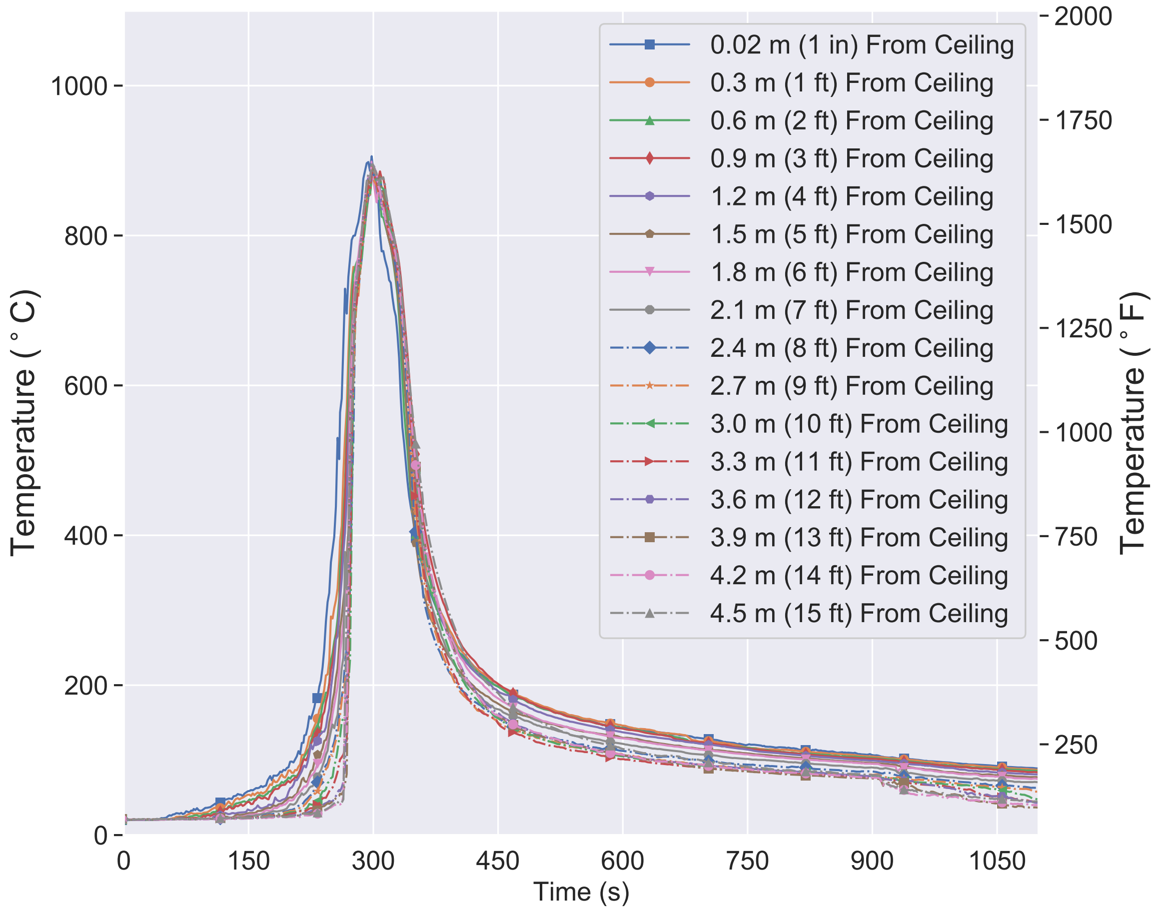
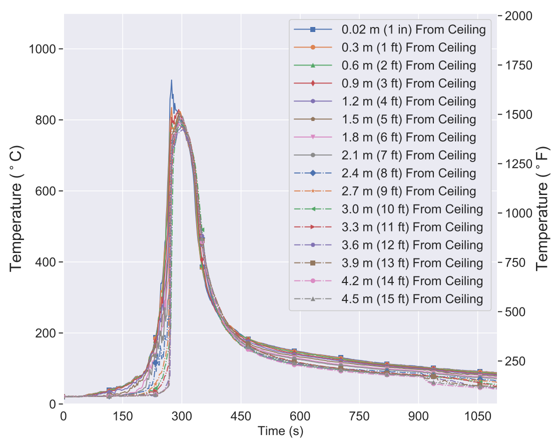
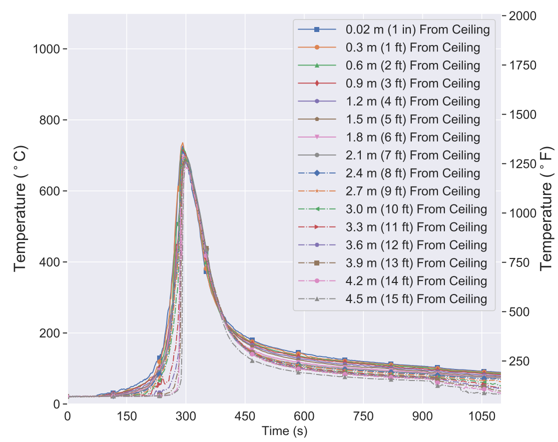


Figure 5.1: Experiment 1, no exterior ventilation openings, family room center temperatures versus time.

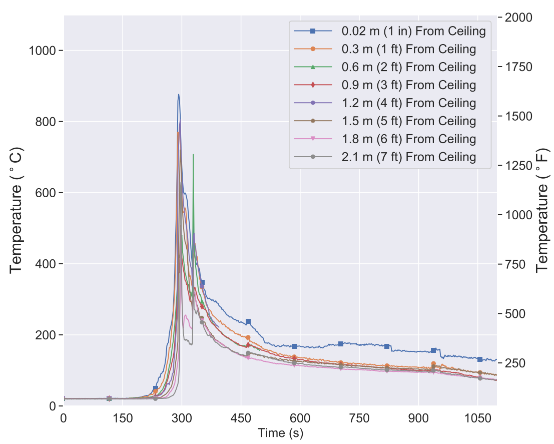
The six graphs shown in Figure 5.2 show the temperatures from the other thermocouples arrays positioned on the lower level. The family room corner and kitchen arrays are located across the rear of the structure. The kitchen temperatures not following the trends are believed to have been damaged when the flames pushed out of the bottom of the family room window opening and ignited some instrumentation wire insulation. The den was also located along the rear of the structure, but the doorway was closed. The rooms on the front side of the structure (i.e., the dining room, foyer and living room) had lower peak temperatures than those in the kitchen or family room.



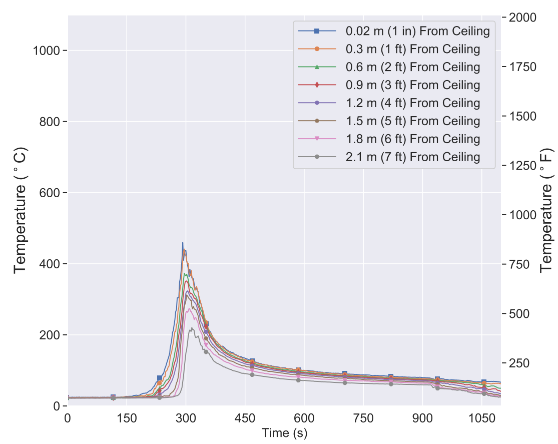
(a) Family Room Corner Temperature



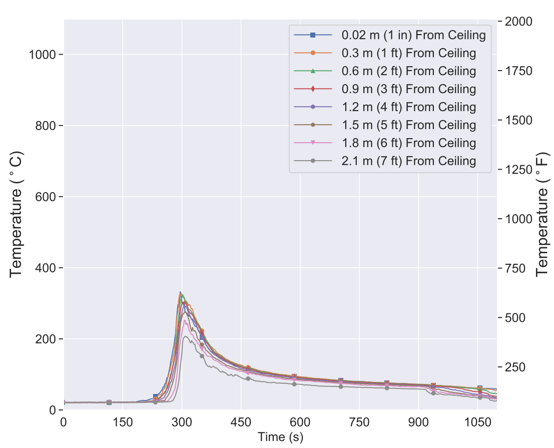
(b) Foyer Temperature



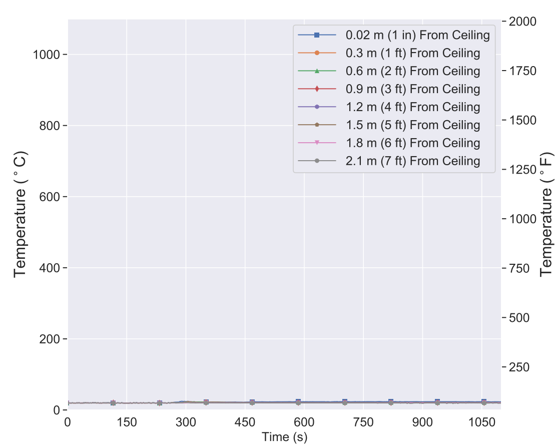
(c) Kitchen Temperature



(d) Dining Room Temperature



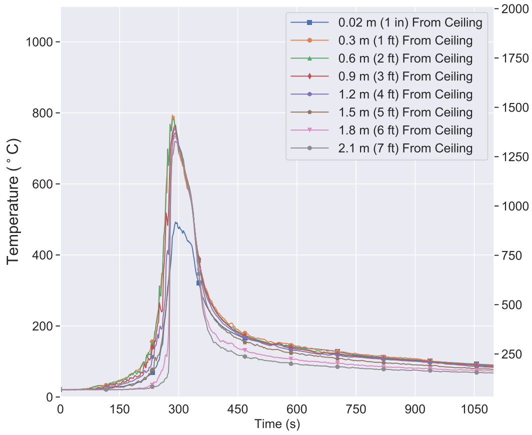
(e) Living Room Temperature



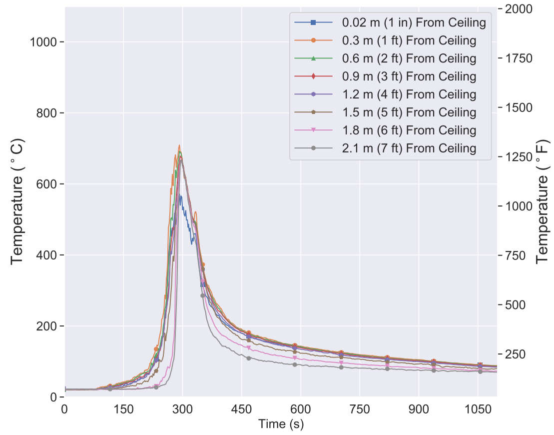
(f) Den Temperature

Figure 5.2: Experiment 1, no exterior ventilation openings, temperature time histories for family room and other first floor rooms.

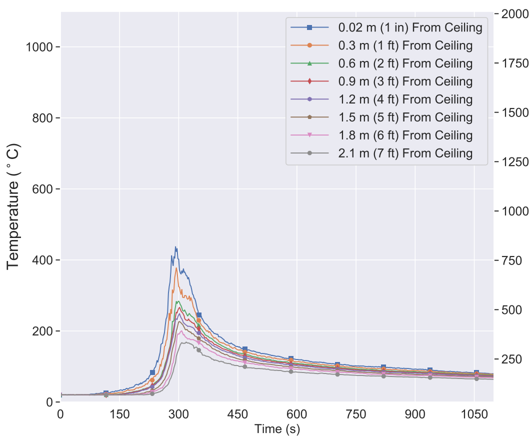
Figure 5.3 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedroom 1 were open to the fire area, and as a result the temperatures follow similar trends in terms of increasing and decreasing with the family room temperatures. In other words, the energy released by the fire in the family room spread throughout all of the open areas of the structure. Bedrooms 1, 2, and 3 were isolated from the fire area by having the doorways closed off, hence there was little to no increase in temperature in the bedrooms.



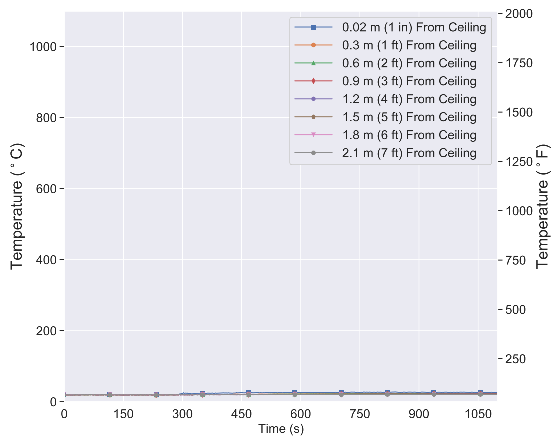
(a) Mid-Hall Temperature



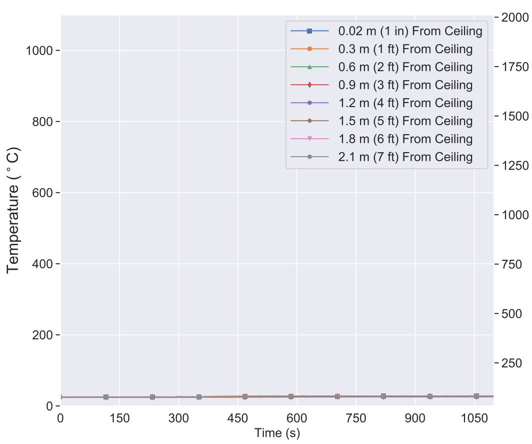
(b) End-Hall Temperature



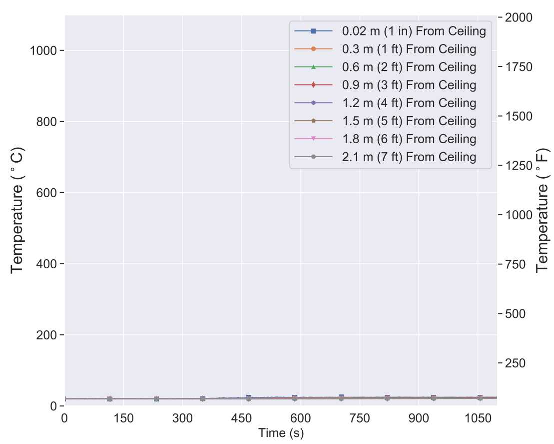
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



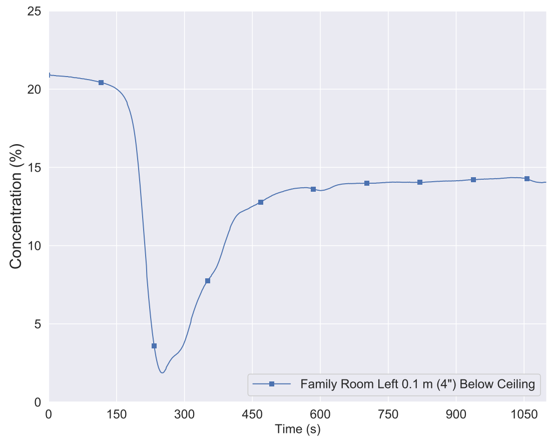
(e) Bedroom 3 Temperature



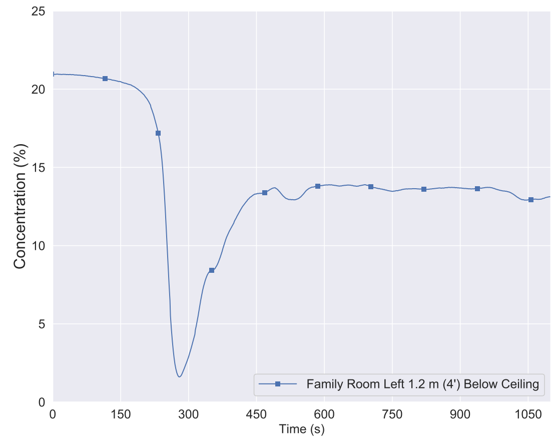
(f) Bedroom 4 Temperature

Figure 5.3: Experiment 1, no exterior ventilation openings, temperature time histories for second floor hallway and bedrooms.

The oxygen concentrations appear in Figure 5.4. The charts shown in Figures 5.4a and 5.4b are from the sampling positions in the family room, located 0.1 m (4 in) and 1.2 m (4 ft) below the ceiling, respectively. As the flames extended to the ceiling, the oxygen levels almost reached zero. The graphs shown in Figures 5.4c and 5.4d are from the sampling positions in the family room, located 1.2 m (4 ft) and 0.1 m (4 in) above the floor, respectively. Once the oxygen levels near the floor reached 15% or lower, the fire started to decrease due to the reduced oxygen level. The oxygen data from the family room left positions were also impacted by the flames burning on the exterior of the structure. After the fire self-extinguished, the oxygen levels began to increase.

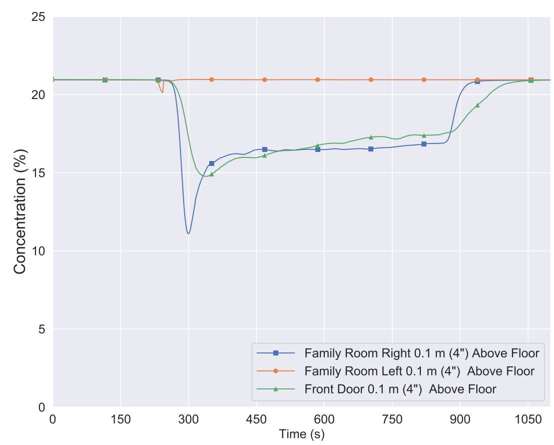


(a) Oxygen 0.1 m Below Ceiling



(b) Oxygen 1.2 m Below Ceiling

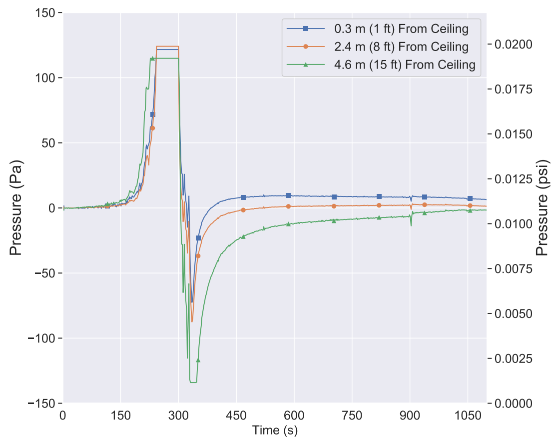
(c) Oxygen 1.2 m Above Floor



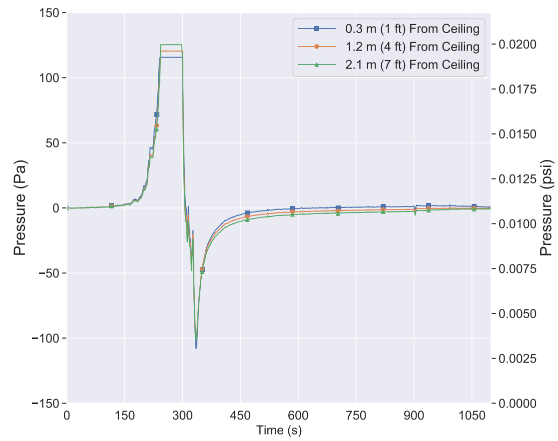
(d) Oxygen 0.1 m Above Floor

Figure 5.4: Experiment 1, no exterior ventilation openings, oxygen concentrations versus time.

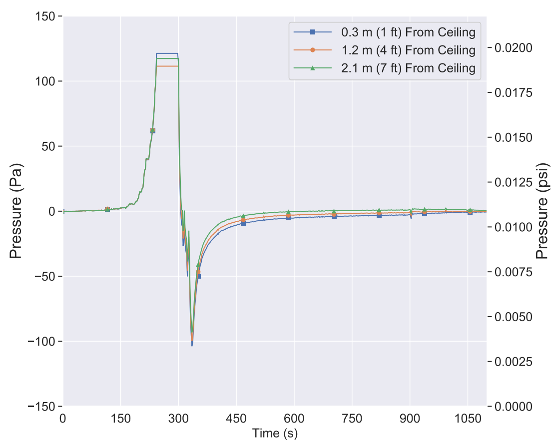
Figure 5.5 shows the pressures from the rooms on the lower level. Notice that as the energy released by the fire increased, the temperature of the gas contained in the structure increased, which caused the gases to expand. This resulted in pressures that exceeded the 125 Pa limit of the pressure transducers. As the heat release rate of the fire decreased, the gas temperatures decreased and the gas contracted, which caused the pressures inside the structure to decrease to at least 100 Pa below atmospheric pressure. In other words, the inside of the structure was essentially under a vacuum relative to the air outside the structure. This pressure difference is the reason fresh air was drawn in through gaps around the doors and windows until the pressures inside and outside equalized. The increase in oxygen concentration within the structure after the fire self-extinguished was another result of the post-flashover pressure difference. The pressure changes in the closed den were less than those in the areas open to the family room.



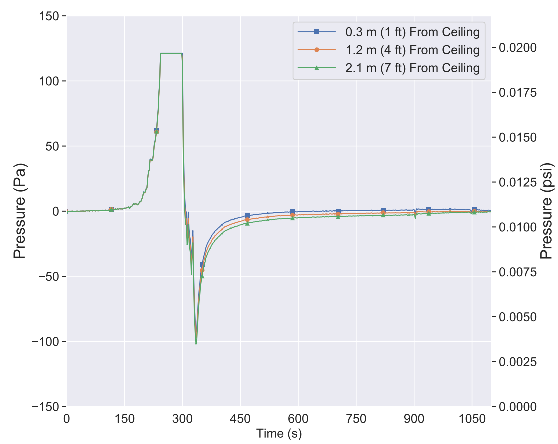
(a) Family Room Pressure



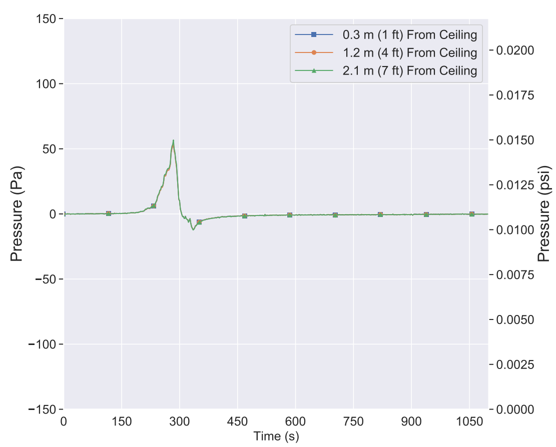
(b) Kitchen Pressure



(c) Front Door Pressure



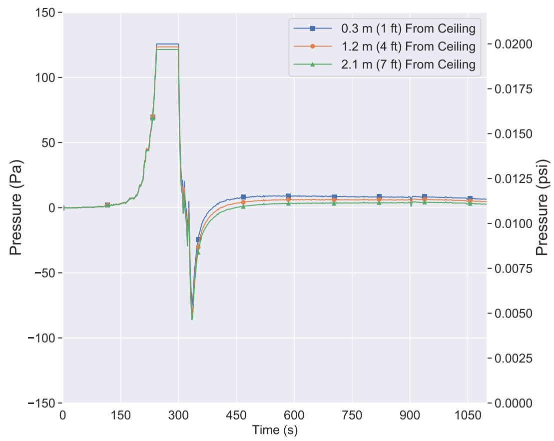
(d) Living Room Pressure



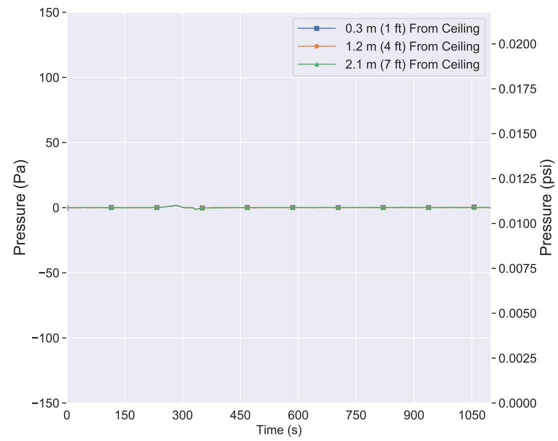
(e) Den Pressure

Figure 5.5: Experiment 1, no exterior ventilation openings, pressures in first floor rooms.

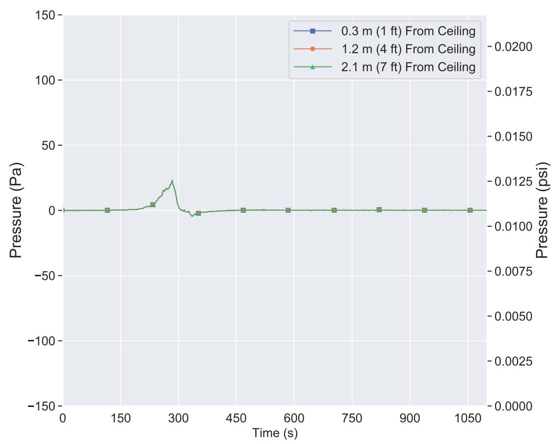
The pressures on the upper level appear in Figure 5.6. Bedroom 1 was the only room open to the fire area. The pressure trends in bedroom 1 are the same as those in the open areas on the first floor. Bedrooms 2, 3, and 4 were closed off from the fire area, which limited the amount of pressure change within those rooms.



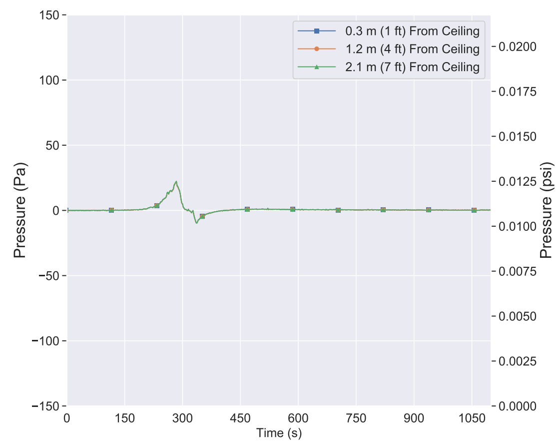
(a) Bedroom 1 Pressure



(b) Bedroom 2 Pressure



(c) Bedroom 3 Pressure



(d) Bedroom 4 Pressure

Figure 5.6: Experiment 1, no exterior ventilation openings, pressures in second floor rooms.

5.1.2 Front Door Open

Experiment 2

An electric match was used to ignite the sofa. As in the previous experiment, the match was positioned at the intersection of the seat cushion, the back cushion, and the right arm of the sofa. As the fire grew, a definitive thermal plume formed, and within 45 s of ignition the flames had extended above the back of the sofa and began to expose the gypsum wallboard. Within 75 s of ignition, the flames had extended vertically and smoke began to spread across the family room ceiling. The fire continued to grow, and within 2 min after ignition, a hot gas layer approximately 0.6 m (2 ft) thick had begun to form on the ceiling of the family room.

As in the first family room experiment, the fire spread along the backside of the sofa and flames extended to the side of the sofa, opposite to the area of origin. So 150 s after ignition, a second fire plume was heating the wall adjacent to the left end of the sofa. At this point in the fire's development, light gray smoke was flowing out of the upper most portions of the open front doorway.

Three minutes after ignition, flames had spread across most of the seat area of the first sofa ignited. The hot gas layer was approximately 3.3 m (10.8 ft) below the family room ceiling. Black smoke was flowing out of the upper half of the open front doorway. After another 30 s, the fire had spread to the second sofa and end table between the two sofas. Black smoke flowed out of the upper two-thirds of the open front doorway. By 225 s after ignition, flames were moving across the ceiling of the family room and black smoke was exhausting out of the entire open front doorway.

The family room transitioned to flashover at 230 s, and there was a noticeable surge of black smoke from the open front doorway from top to bottom. By 270 s after ignition, a bi-directional flow was stabilized at the front doorway with smoke flowing out of the upper three-quarters of the doorway. The family room continued to burn.

At 5 minutes after ignition, the fire in the family room began to decrease, and black smoke exited only from the upper half of the doorway as more fresh air entered the house through the lower half. A minute later, most of the fire in the family room was burning near the floor and side C (i.e., the back wall), near the upholstered chairs. No flames were visible higher than 1 m (3.3 ft) above the floor.

There was increased burning in the second upholstered chair (furthest from the ignition sofa) at 450 s after ignition as black smoke continued to flow out of the upper half of the front doorway. At 10 min into the experiment, the fire and exhaust flow conditions remained steady. The fire in the family room decreased in size at 690 s after ignition, most of the upholstery material appeared burnt away, and all remaining visible flames appeared near the floor. Fifteen minutes after ignition, firefighters opened the family room window shutters and began suppression of the flames in the family room. The fire was extinguished in a matter of seconds. Table 5.3 shows the timeline of events for Experiment 2.

Table 5.3: Timeline for Experiment 2, Family Room Fire with Front Door Open

Time (s)	Event
0	Ignition on right side of sofa.
45	Flames extend past the top of the back of the sofa, gypsum board exposed to flame.
75	Flames extend vertically, smoke flowing across ceiling in family room.
120	HGL building across family room ceiling, approximately 0.6 m thick.
150	Fire has spread along the back side of the sofa, flames have extended to the side of the sofa opposite the area of origin, and light gray smoke is exiting the upper most portions of the open front doorway
180	Flames have spread across most of the seat area of first sofa ignited, HGL is approximately 3.3 m below the family room ceiling, and black smoke is flowing out of upper half of open front doorway
210	The fire has spread to second sofa and end table, and black smoke is flowing out of upper two-thirds of open front doorway
225	Flames moving across the ceiling of the family room, and black smoke appears to be exhausting out of the entire open front doorway
230	Furnished portion of the family room is transitioning to flashover, and noticeable push of black smoke from the open front doorway, top to bottom
270	Steady burning in family room, bi-directional flow has stabilized at the front doorway, and black smoke exiting the upper three-quarters of the doorway.
300	Fire in family room is decreasing and black smoke exiting the upper half of the doorway
360	Most of fire in family room is burning near the floor and side C near the upholstered chairs. No flames were visible 1 m above the floor
450	Increased burning in the second upholstered chair (furthest from the ignition sofa. Black smoke still exiting the upper half of the front doorway
600	Fire and exhaust flow conditions have remained steady
690	Fire in family room decreasing in size, most of the upholstery material appears to have burned away and all visible flames appear near the floor
900	Firefighters open family room window shutters and begin suppression in family room
910	Fire extinguished

Figure 5.7 displays the time history of the temperatures of the thermocouple array positioned in the center of the family room, the array closest to the point of ignition. The graph shows the build up of the hot gas layer from the ceiling down to the floor in the first 225 s after ignition. Seconds later the temperatures in the area of the thermocouple array exceeded 800 °C (1472 °F) and stayed at the level for approximately one minute before decreasing. Approximately 5 min after ignition, the temperatures in the living room began to stratify. Temperatures near the floor decreased by more than 500 °C (932 °F) over a period of less than 30 s. While the rapid decrease in temperature was seen in the previous experiment, this experiment exhibited continued burning that slowed the decrease in the temperatures closer to the ceiling, keeping them above 600 °C (1112 °F) until 500 s

after ignition. The thermal gradient was reduced after this point and continued to get smaller until the firefighters vented the fire room 15 min after ignition. The missing section of the data traces are an artifact of an intermittent data acquisition system malfunction.

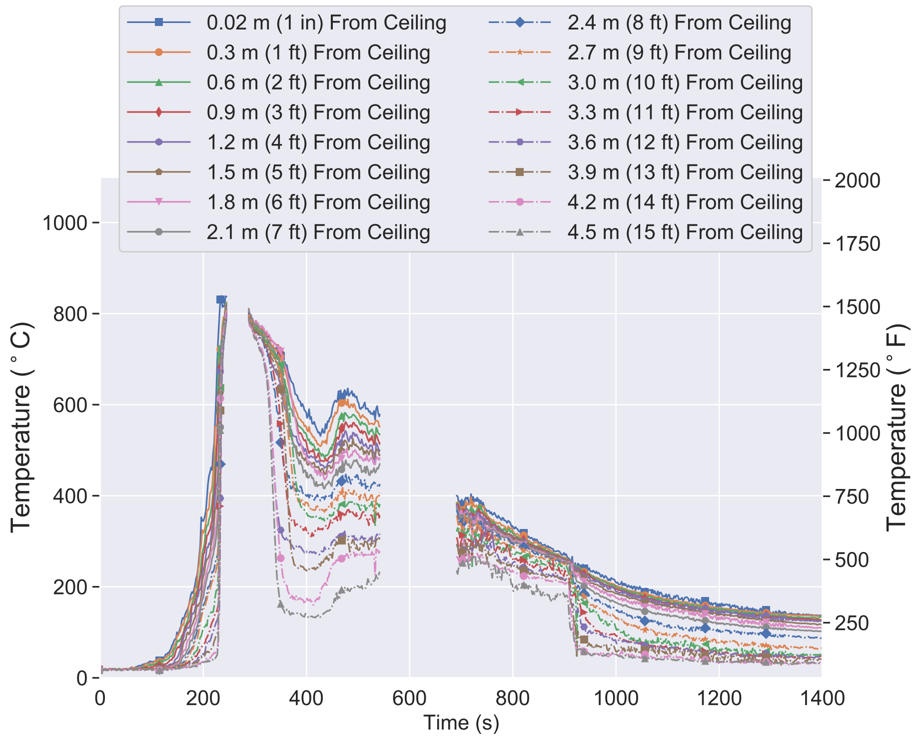


Figure 5.7: Experiment 2, no exterior ventilation openings, family room center temperatures versus time.

The front door temperatures for Experiment 2 are given in Figure 5.8. The temperatures of the gases flowing through the front door remained stratified during the fire growth period until firefighter intervention. It appears that no flames passed through the door based on the peak hot gas temperature of approximately 500 °C (932 °F). The trends of the temperature increases and decreases track along with the temperatures in the family room.

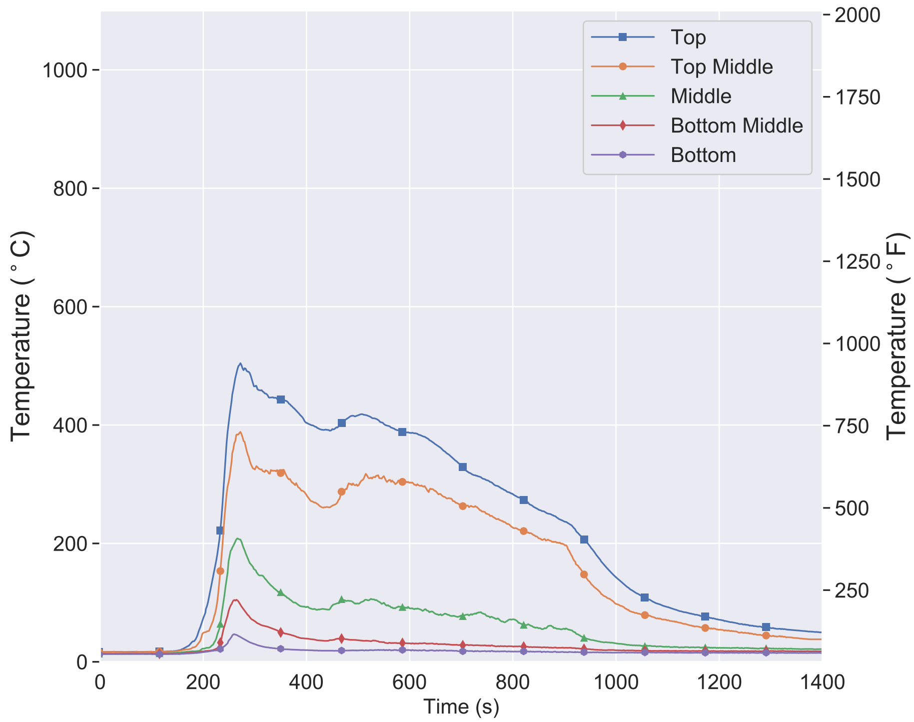
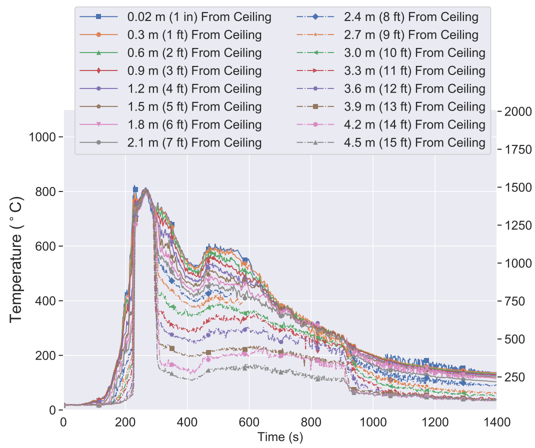
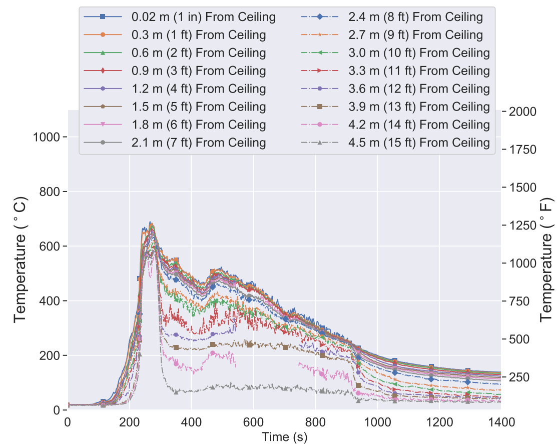


Figure 5.8: Experiment 2, front door open, front door temperatures versus time.

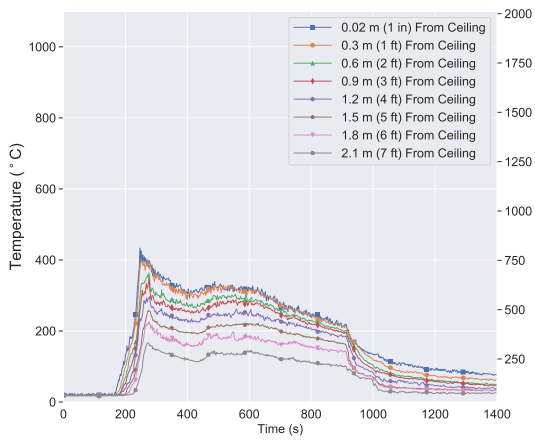
The six graphs in Figure 5.9 are the temperatures from the other thermocouples arrays positioned on the lower level. All of the temperature graphs show evidence of a longer fire burning time, relative to Experiment 1. The family room corner and foyer arrays are both 4.88 m (16 ft) high and have the best agreement with the temperatures from the center of the family room. The other three rooms open to the family room have 2.44 m (8 ft) ceilings. The kitchen and the dining room (Figures 5.9c and 4.7a) have similar peak temperatures and temperature ranges. This may be a function of the doorway that leads from the kitchen into the dining room. The living room (Figure 5.9e) has the lowest peak temperatures on the lower level. This may be a result of the living room being remote from the open front door and out of the main paths of gas flow between the seat of the fire and the exterior vent. The den temperature did not increase because it was closed off from the fire area.



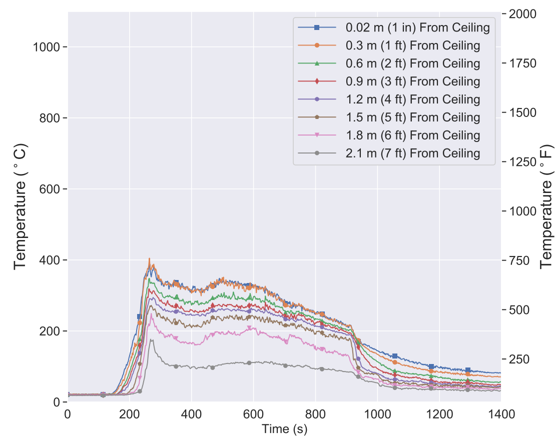
(a) Family Room Corner Temperature



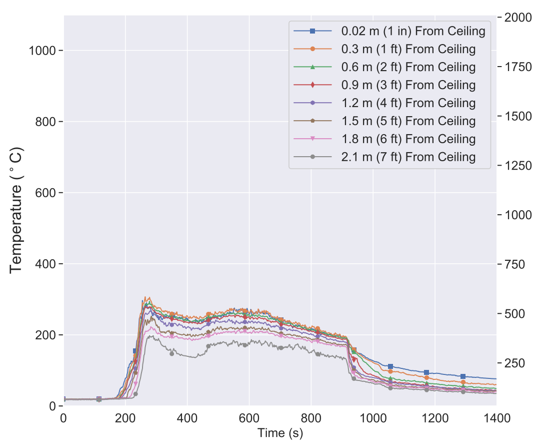
(b) Foyer Temperature



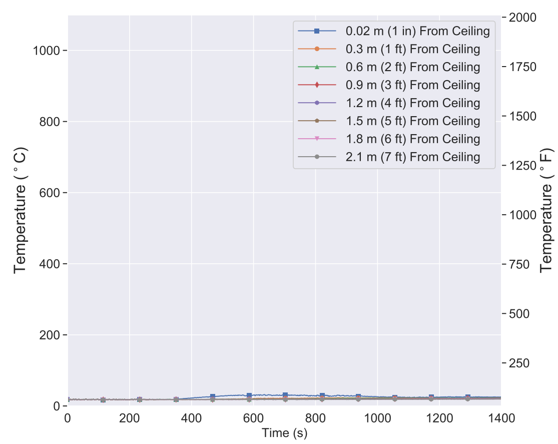
(c) Kitchen Temperature



(d) Dining Room Temperature



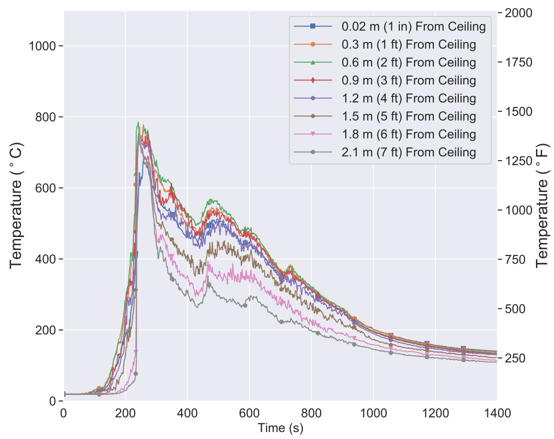
(e) Living Room Temperature



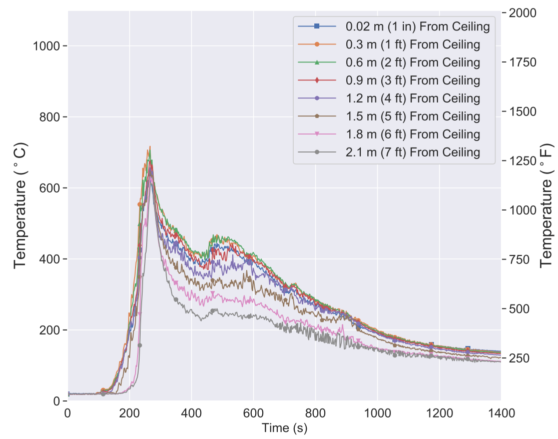
(f) Den Temperature

Figure 5.9: Experiment 2, front door open, temperature time histories for family room and other first floor rooms.

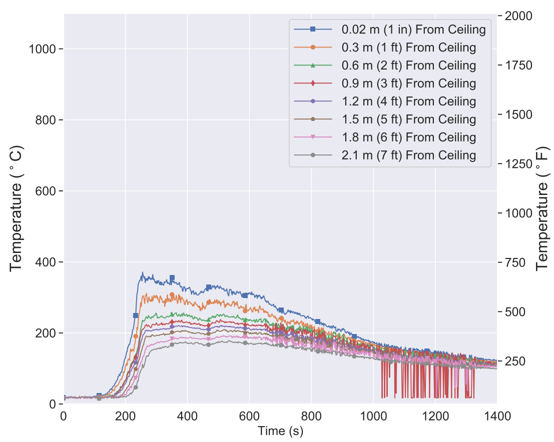
Figure 5.10 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedroom 1 were open to the fire area. The mid-hall array temperatures shown in Figure 5.10a had the most similar temperatures and trends as the temperatures in the family room. This array is also in the direct exhaust flow of the hot gases as they flowed from the family room into the foyer and down toward the open front door. As the distance from the mid-hall position increased while moving toward bedroom 1, the temperatures tended to decrease. Bedroom 1, much like the living room, is not part of the main fire flow paths and therefore has lower temperatures than the hallway arrays. Bedrooms 2, 3, and 4 were isolated from the fire area by having the doorways closed off, hence there was little to no increase in temperature in the bedrooms.



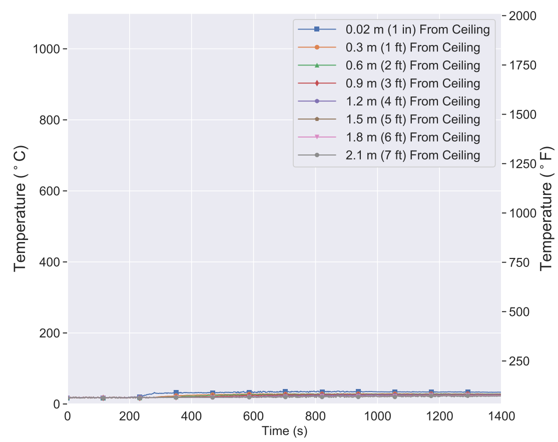
(a) Mid-Hall Temperature



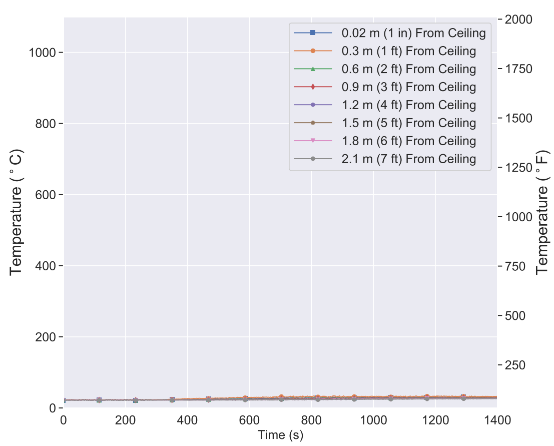
(b) End-Hall Temperature



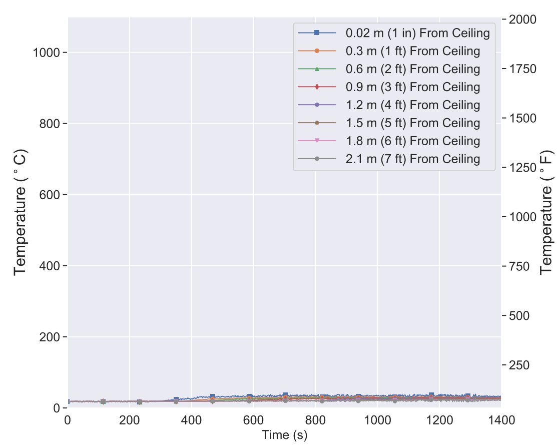
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature



(f) Bedroom 4 Temperature

Figure 5.10: Experiment 2, front door open, temperature time histories for second floor hallway and bedrooms.

The velocity time history from the open front door appears in Figure 5.11. The increase in the velocity of gases exiting the front doorway is consistent with the growth rate of the fire based on the temperature increase in the family room. Peak exhaust velocities ranging from 8 m/s (17.6 mph) near the top of the door to 5 m/s (11 mph) near the bottom of the door support the observation of the noticeable push of black smoke out of the front door at approximately 230 s after ignition. After the instability exhibited during flashover, the doorway resumes its function as a bi-directional vent, vent with an exhaust for hot gas and an air intake.

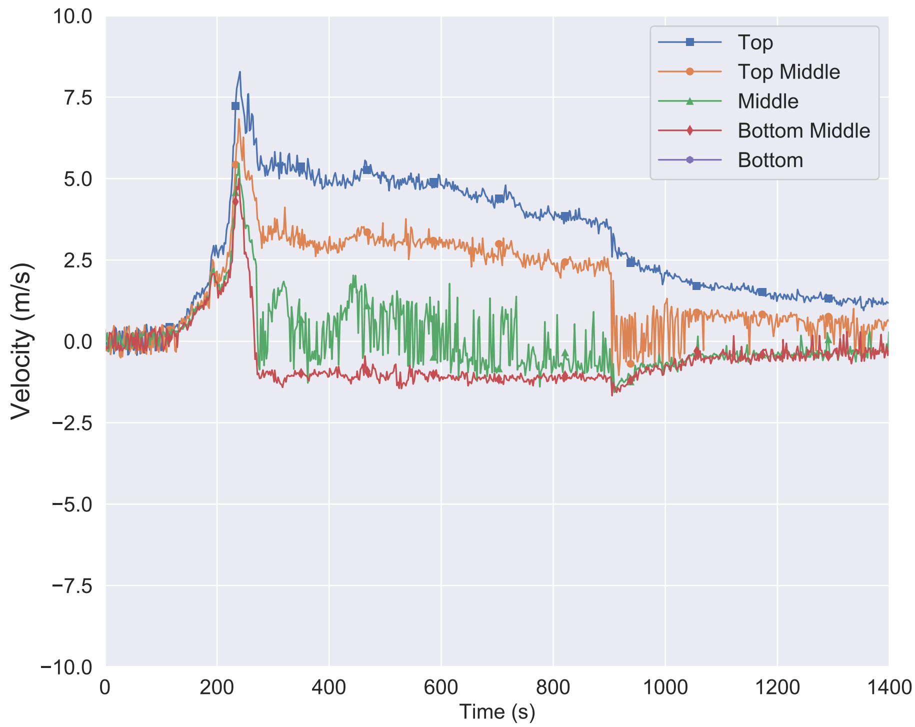
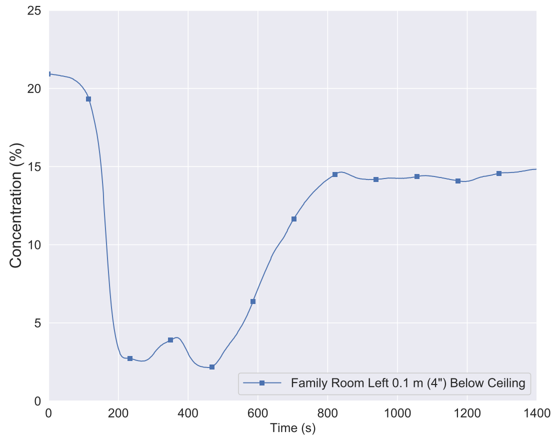


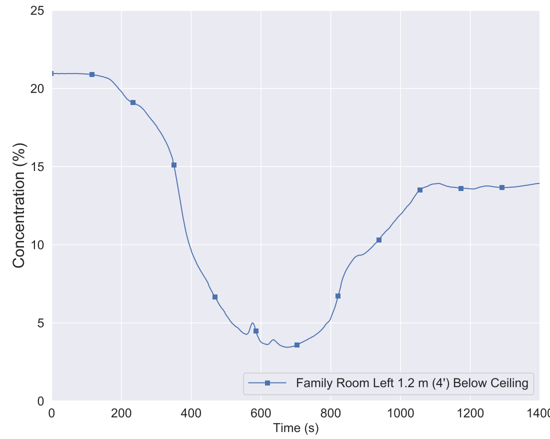
Figure 5.11: Experiment 2, front door open, front door velocity versus time.

The oxygen concentrations appear in Figure 5.12. The charts shown in Figures 5.12a and 5.12b are from the sampling positions in the family room, located 0.1 m (4 in) and 1.2 m (4 ft) below the ceiling, respectively. As the flames extended to the ceiling, the oxygen concentrations decreased below 5%. The oxygen concentrations at these positions remained below 5% post-flashover, for at least 5 min. Perhaps this is due to the continued burning and a lack of exhaust vent on the upper level.

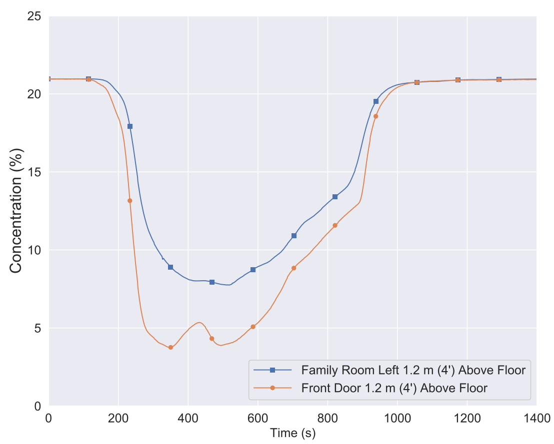
Figures 5.12c and 5.12d are from the sampling positions in the family room, located 1.2 m (4 ft) and 0.1 m (4 in) above the floor, respectively. As the fire was approaching flashover, oxygen-depleted gases were pushed over the oxygen sampling position near the front door and 1.2 m (4 ft) above the floor. The lowest oxygen concentration at this location, below 5%, first occurred about 340 s after ignition, during the fire decay stage. The 1.2 m (4 ft) above the floor oxygen sampling position in the family room trailed the decreases shown at the front door position, indicating that the hot gas layer descended later than the layer elevation near the front door. Further, the oxygen concentration in living room remained higher than in the foyer by the front door. Finally, the oxygen concentrations near the floor, Figure 5.12d, remained at or above 20%. The front door provided for an exhaust vent, such that the hot gas layer did not fill the lower layer as it did in the previous experiment with no exterior vents, and the front door provided some amount of fresh air to the structure during most of the experiment.



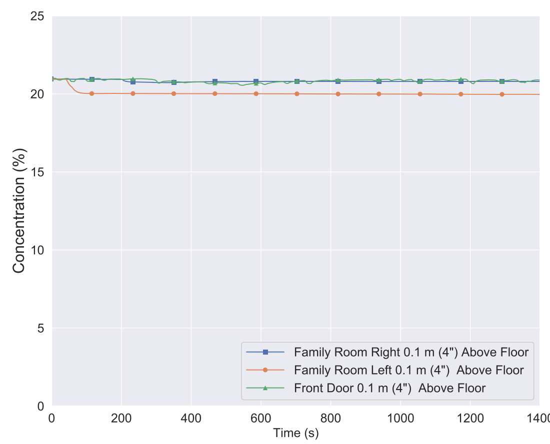
(a) Oxygen 0.1 m Below Ceiling



(b) Oxygen 1.2 m Below Ceiling



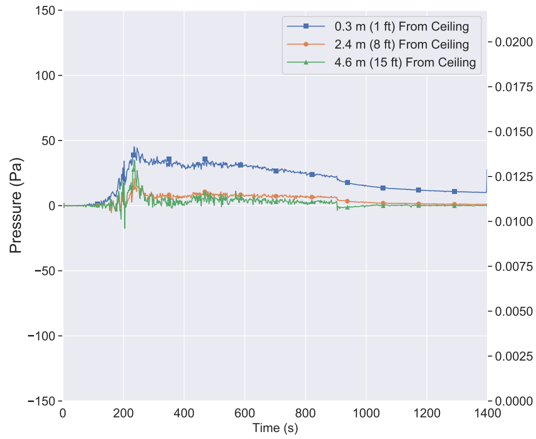
(c) Oxygen 1.2 m Above Floor



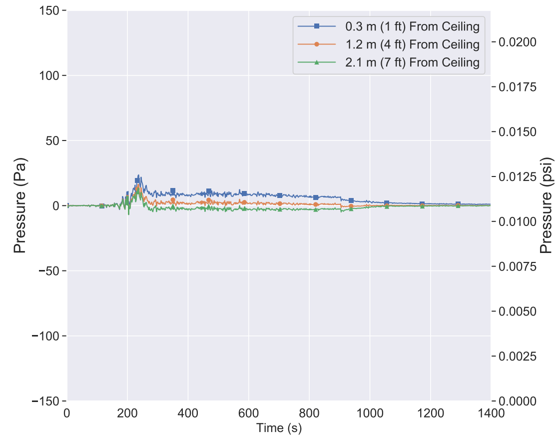
(d) Oxygen 0.1 m Above Floor

Figure 5.12: Experiment 2, front door open, oxygen concentrations versus time.

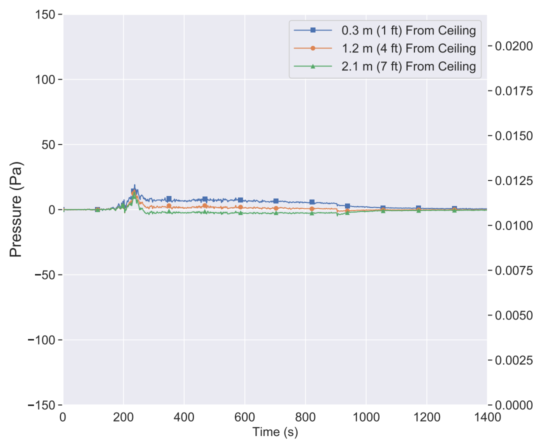
Figure 5.13 shows the pressures from the rooms on the lower level. The open front door provided not only an exhaust and intake vent, it also served as a pressure-relief vent. The peak pressure in the family room was less than 50 Pa. The family room pressures were also the peak pressures in the structure. The pressure gradient with the higher pressures near the ceiling and the lower pressures near the floor was more pronounced than in the closed door experiment. The gas pressures increased as the gas temperatures increased (gas expansion) and decreased as the gas temperatures decreased (gas contraction). The pressure difference between the ceiling and floor and between different areas of the structure resulted in gas movement from areas of higher pressure to areas of lower pressure via flow paths. The slightly negative pressure post-flashover in the kitchen, living room, and front door positions near the floor allowed for the higher pressure outside air to flow into the structure. In this experiment, the den was closed off from the fire area, so the pressure in the den did not change.



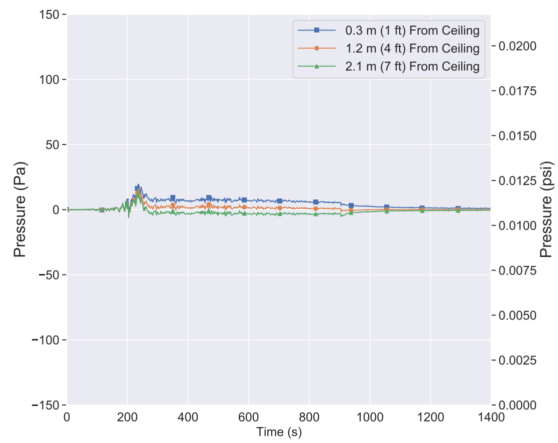
(a) Family Room Pressure



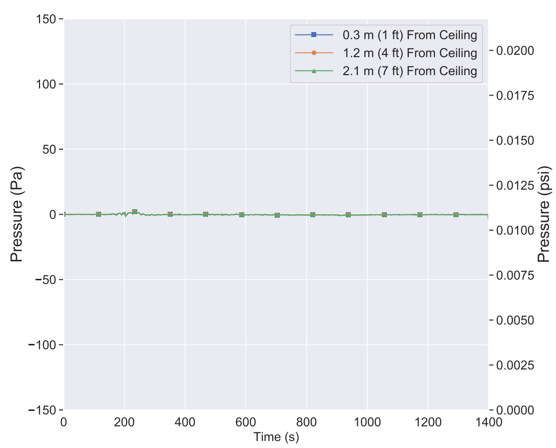
(b) Kitchen Pressure



(c) Front Door Pressure



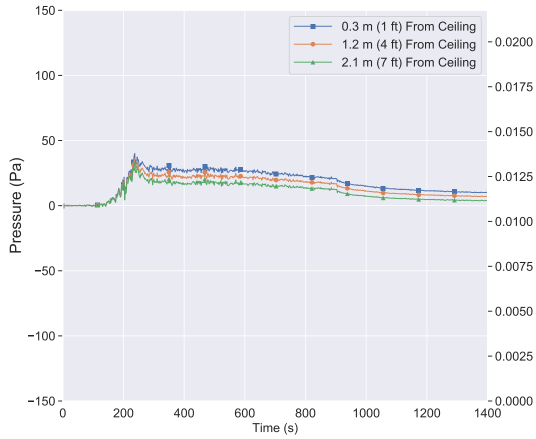
(d) Living Room Pressure



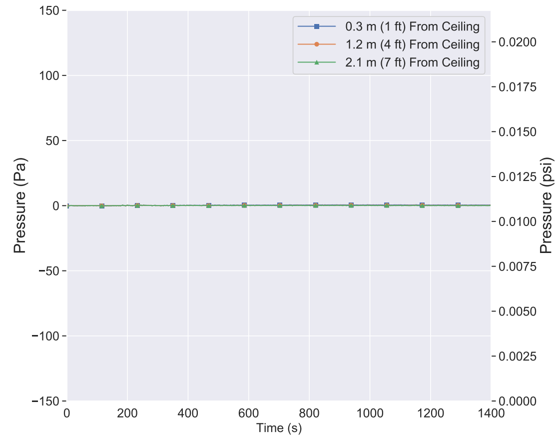
(e) Den Pressure

Figure 5.13: Experiment 2, front door open, pressures in first floor rooms.

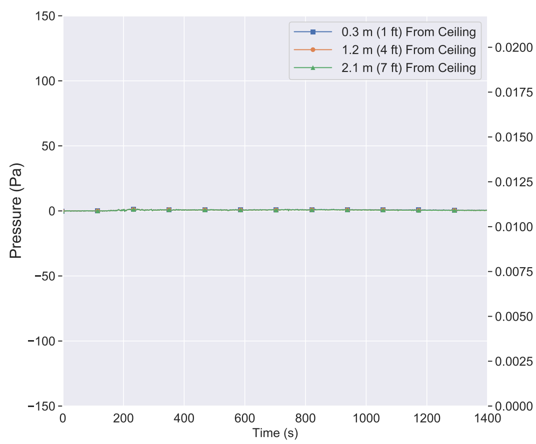
The pressures on the upper level appear in Figure 5.14. Bedroom 1 was the only room open to the fire area. The pressure trends in bedroom 1 were similar to the pressure in the upper portion of the family room. Bedroom 1 had a positive pressure from fire growth through firefighter intervention. Bedrooms 2, 3, and 4 were closed off from the fire area, which resulted in little to no pressure change within those bedrooms.



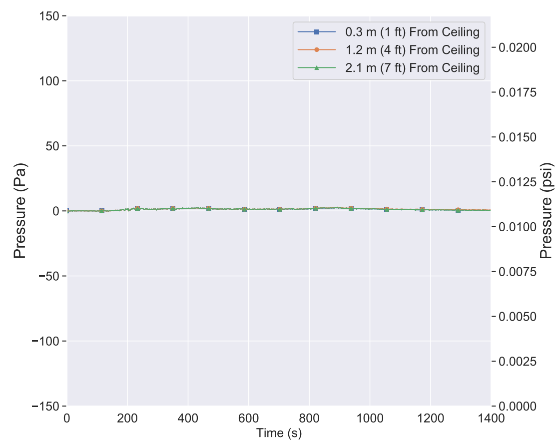
(a) Bedroom 1 Pressure



(b) Bedroom 2 Pressure



(c) Bedroom 3 Pressure



(d) Bedroom 4 Pressure

Figure 5.14: Experiment 2, front door open, pressures in second floor rooms.

5.1.3 Front Door and Bedroom 3 Door and Window Open

Experiment 3

The experiment timeline began with the ignition of an electric match on the sofa. Within 30 s after ignition, the flames had extended above the back of the sofa and the gypsum wallboard was exposed to the heat from the flame. The fire on the sofa continued to grow, involving a portion of the right arm and the seat and back cushions. Visible smoke had begun to spread across the family room ceiling within 90 s of ignition.

Two minutes after ignition, the flames had extended to approximately 1.2 m (4 ft) above the back of the sofa and the base of the fire was about 0.6 m (2 ft) square. The hot gas layer had begun to form on the ceiling of the upper level and was flowing into bedroom 3 through the open doorway. About 30 seconds later, light smoke was also observed exiting bedroom 3 via the open window. No smoke was observed flowing out of the front door at this time.

The sofa fire behavior was repeatable in the sense that the fire typically burned through the back of the sofa near the point of ignition and then the flames spread along the back so that a second thermal plume was evident on the side of the sofa opposite the point of ignition. The two plumes coexisted for about 30 s prior to merging into one as the full seating area of the sofa became involved in flames at 3 min and 30 s after ignition. Black smoke was being exhausted from most of the height of the open bedroom window, while smoke was also exiting the upper 0.3 m (1 ft) of the open front door.

Four minutes after ignition, the radiation from the flames on the ignition sofa began to pyrolyze the adjacent sofa. The end table between the sofas was already burning. Black smoke continued to flow out of upper portion of open front doorway and most of the open bedroom window. Black smoke was flowing out of upper portion of open front doorway and most of the open bedroom window.

Seconds later the second sofa ignited. The fire in the family room had started the transition to flashover. Smoke flow out of both the front door and the bedroom window had increased.

At 270 s after ignition, flames were extending across the family room ceiling into the foyer and into bedroom 3. Flames were observed exiting the bedroom 3 window. The hot gas layer was within 0.5 m (1.6 ft of the floor) on the lower level of the structure, and the neutral plane in the front door had dropped to within 1 m (3.3 ft) of the floor. Black smoke was pushing out of the upper portion of the front doorway. Hot gases were flowing down the stairs into the lower level.

Post-flashover burning continued in the family room, in the foyer, and in bedroom 3. At 5 min after ignition, the black smoke shrouding the orange glow of flames was seen in the front doorway and the bedroom 3 window. Smoke inside the structure was still within 0.5 m (1.6 ft of the floor) on the lower level of the structure, but the neutral plane in the front door had lifted such that smoke was exiting only out of the upper third of the doorway.

By six minutes after ignition, the fire appeared to decrease in size in the family room. The smoke flow out of the open bedroom window also seemed to be pulsing. As the fire in the family room continued to burn, on the exterior of the structure, backside small flames developed above the family room window shutter that was the most remote from the area of origin. Smoke was also leaking from the gap in the kitchen doors.

Hot gases pushing down from the upper level via the foyer appeared to be recirculating within the structure at 7 min after ignition. At the same time, the smoke flow out of the front doorway was reduced in volume and density. The bottom of the hot gas layer was approximately 1.2 m (4 ft) above the lower level floor.

Burning continued in family room and bedroom 3. Fire in family room appeared to be transitioning from vent controlled to fuel controlled, although ventilation controlled burning seemed to be occurring in bedroom 2. Small flames continued to burn on the exterior above family room window shutter. Nine minutes after ignition, firefighters started to flow water into the foyer and family room through the front door. About 15 s later, other firefighters opened the burning family room window shutter to extinguish the fire on the shutter, and then flowed water into the family room. Family room fire suppression stopped at 9 min and 40 s after ignition. Approximately 10 min and 30 s after ignition, firefighters entered the structure through the front door and went upstairs and found that fire was still burning in bedroom 3. Within a minute, extinguishment was completed. The timeline for this experiment is shown in Table 5.4.

Table 5.4: Timeline for Experiment 3, Family Room Fire with Front Door and Bedroom 3 Window Open

Time (s)	Event
0	Ignition on right side of sofa
30	Flames extend above the top of the back of the sofa, exposing gypsum board
90	Flames have extended vertically. Smoke flowing across family room ceiling
120	Fire limited to one seat of the sofa with flames approximately 1.2 above the sofa, HGL building across second floor ceiling and flowing into bedroom 3
180	Fire has spread along the back side and under the sofa, and a second plume extends from the left side of the sofa
205	Small amount of light gray smoke is exiting the open front doorway
210	Flames have spread across the seat area of ignition sofa, plumes merged into one, flames approximately 3.5 m above the floor, HGL building under the first floor ceiling
240	Flames have spread to end table, adjacent sofa is pyrolyzing, black smoke is flowing out of upper portion of open front doorway and most of the open bedroom window
245	The fire has spread to second sofa
255	Fire in family room transitioning through flashover
260	Fire in family room continues to grow, flames flowing across family room ceiling, smoke flow out of open bedroom window and front door is increasing
270	Flames across second floor hallway connecting family room to foyer and extending into Bedroom 3, HGL on the lower level appears to be approximately 0.5 m above the floor
285	Post-flashover burning continues in family room and bedroom 3
300	Smoke continues to flow out of the front door, bedroom 3 window smoke flow fills the window top to bottom
360	Fire appears to decrease in family room
400	Flames visible on the exterior above the family room window shutter, the most remote from the area of origin
420	Hot gases pushing down from the upper level to approximately 1.2 m above the lower level floor, smoke flow out of the front doorway reduced in volume and density
510	Burning continued in family room and bedroom 3, fire in family room appears to be fuel controlled, flame continues on the exterior above family room window shutter
540	Fire suppression begins with water flow through open front doorway
555	Firefighters open family room window shutter begin suppression
580	Fire extinguished in family room
630	Fire continues to burn in bedroom 3
660	Fire growing in bedroom 3
670	Bedroom fire suppression started
690	Fire extinguished

Figure 5.15 displays the time history of the temperatures of the thermocouple array positioned in the center of the family room, the array closest to the point of ignition. The graph shows the build up of the hot gas layer from the ceiling down to the floor in the first 250 s after ignition. Seconds later, the temperatures in the area of the thermocouple array exceeded 1000 °C (1832 °F). The peak temperatures in the family room remained above 800 °C (1472 °F) for about 4 minutes before decreasing further. Approximately 9 min after ignition, the temperatures in the living room began decrease at a faster rate due to the start of suppression.

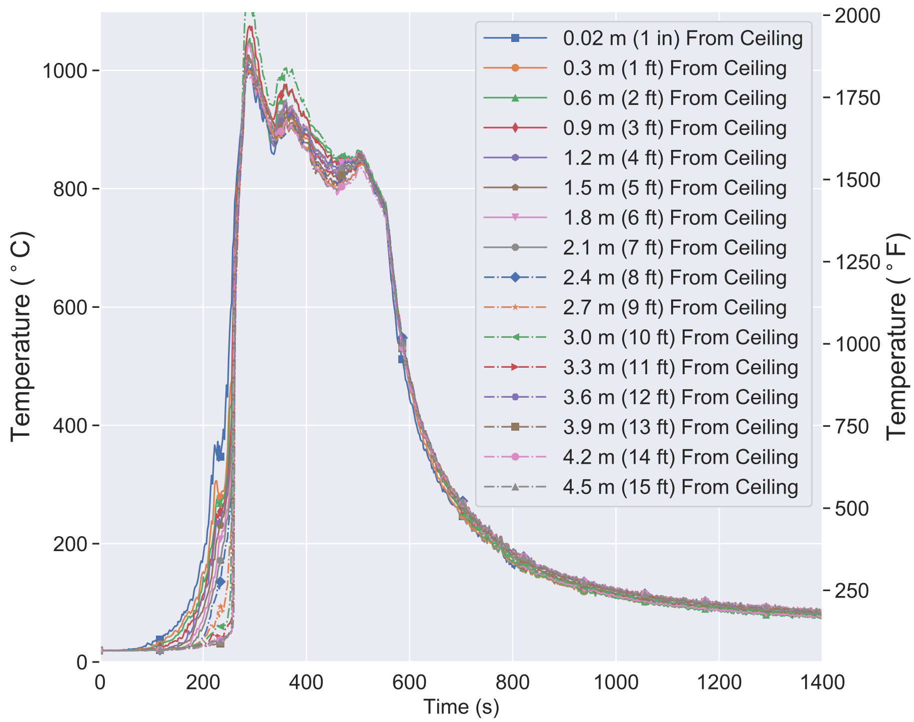


Figure 5.15: Experiment 3, front door, bedroom 3 door and window open, family room center temperatures versus time.

The front door temperatures for Experiment 3 appear in Figure 5.16. Once the heated gases were flowing through the front door, the temperature remained stratified throughout the fire until fire suppression. The peak temperature in the upper portion of the doorway was 560 °C (1040 °F). The minimum temperature of gas that flowed out of the door during the fully developed fire stage was in the lower portion of the door, 44 °C (111 °F). The trends of the temperature increases and decreases track along with the temperatures in the family room.

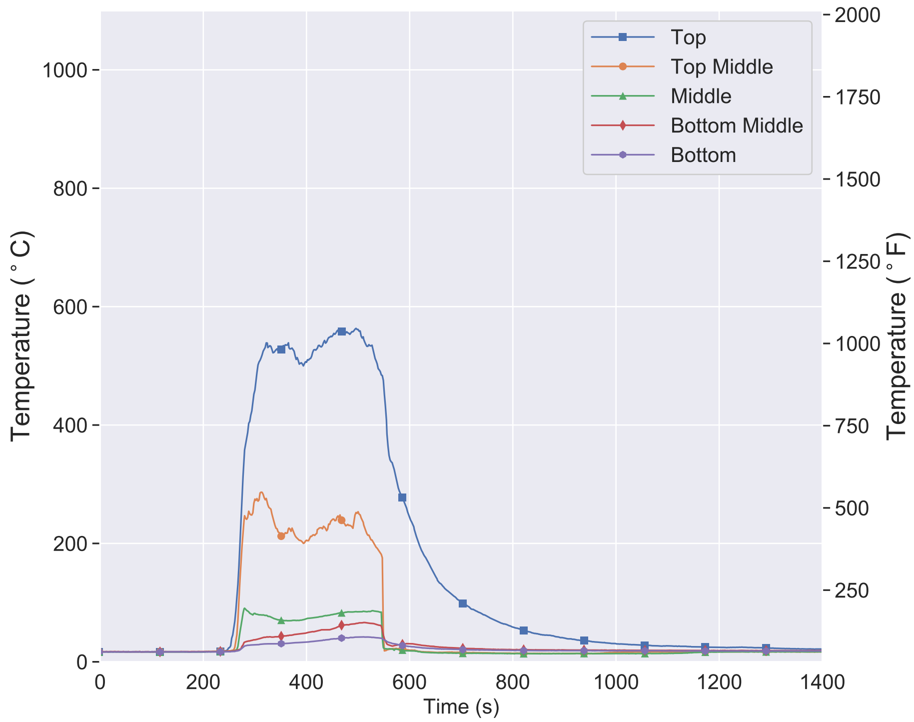


Figure 5.16: Experiment 3, Front door, bedroom 3 door and window open, front door temperatures versus time

The bedroom 3 window temperatures for Experiment 3 appear in Figure 5.17. The peak temperature in the upper portion of the window was approximately 600 °C (1112 °F). The minimum temperature of gas that flowed out of the window during the fully developed fire stage was in the lower portion of the window, 440 °C (824 °F). The trends of the temperature increases and decreases track along with the temperatures of the source fire up to the time of initial fire suppression in the family room, which occurred between 540 s and 580 s after ignition. After this point, the fire in Bedroom 3 re-grew. This caused the late increase in temperatures at the bedroom window that is inconsistent with the temperature trends of the family room source fire.

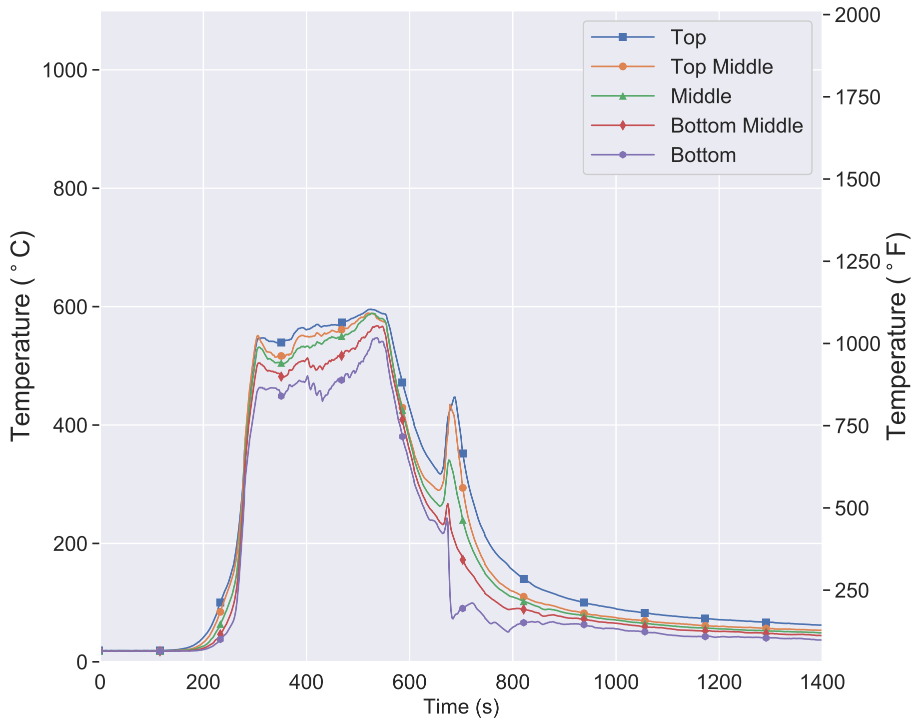
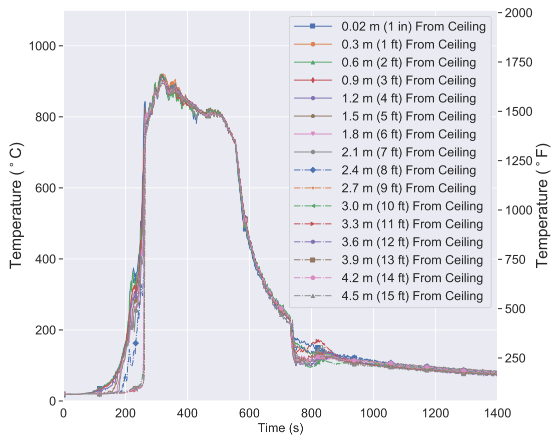


Figure 5.17: Experiment 3, front door, bedroom 3 door and window open, bedroom 3 window temperatures versus time.

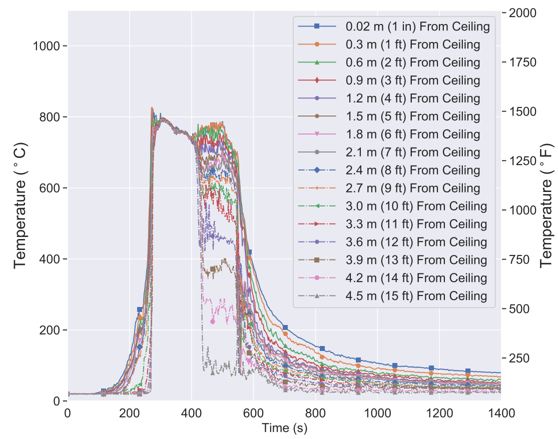
The six graphs in Figure 5.18 show the temperatures from the other thermocouple arrays positioned on the lower level. All of the temperature graphs show evidence of a longer burn time (compared to the two previous experiments) at conditions that were in excess of 600 °C (1112 °F) from the ceiling down to near floor level in the family room. The family room corner and foyer arrays are both 4.88 m (16 ft) high and have the best agreement with the temperatures from the center of the family room.

The other three rooms open to the family room have 2.44 m (8 ft) ceilings. The kitchen, dining room, and living room (see Figures 5.18c, 5.18d, and 5.18e) have similar temperature ranges and trends. The den had no temperature increase as a result of being closed off from the fire area.

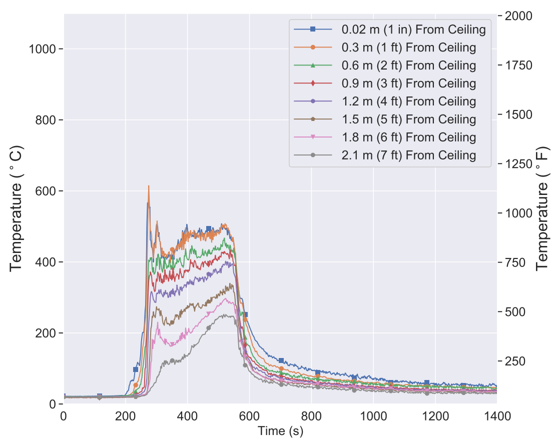
Figure 5.19 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway, bedroom 1, and bedroom 3 were open to the fire area. The graphs from the two thermocouple arrays in the hall (see Figures 5.19a and 5.19b), and the temperature graph from bedroom 3 all exhibited flashover fire conditions. These arrays were in the direct exhaust flow of the hot gases as they flowed from the family room into bedroom 3 or the foyer and then down toward the open front door. The temperatures in bedroom 1 (see Figure 5.19c) were less than the other areas open to the fire room and did not approach flashover conditions. Bedroom 1 was not in the main exhaust portion of the fire flow paths and therefore saw lower temperatures than the arrays that were between the fire exhaust and an exhaust vent. Bedrooms 2 and 4, were isolated from the fire area by having the doorways closed off, so there was little to no increase in temperature in those



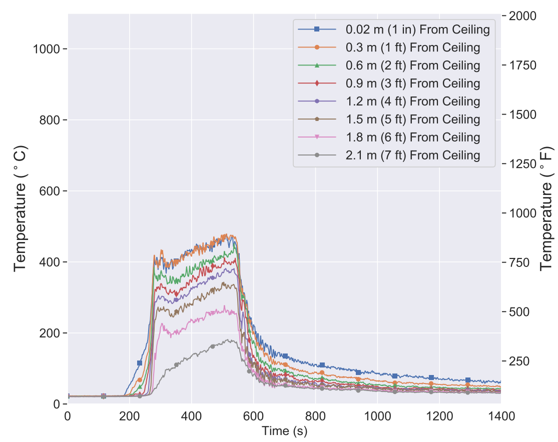
(a) Family Room Corner Temperature



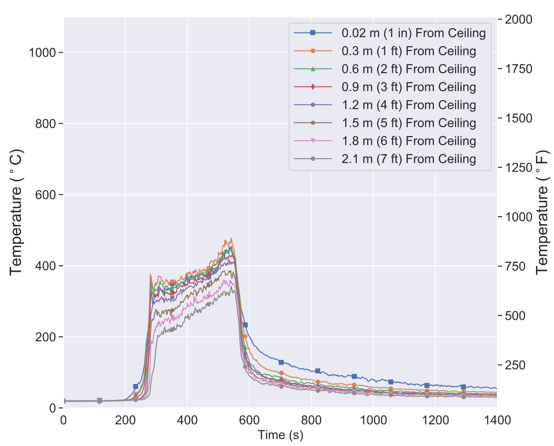
(b) Foyer Temperature



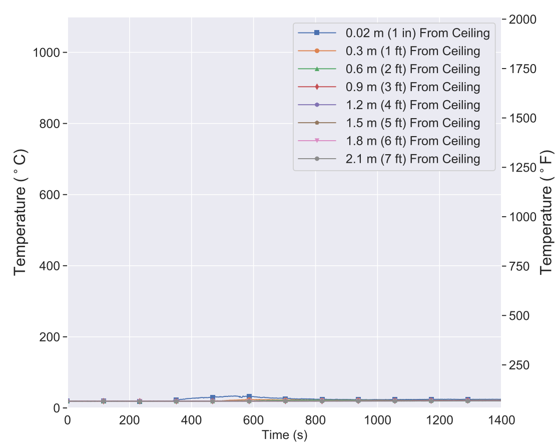
(c) Kitchen Temperature



(d) Dining Room Temperature



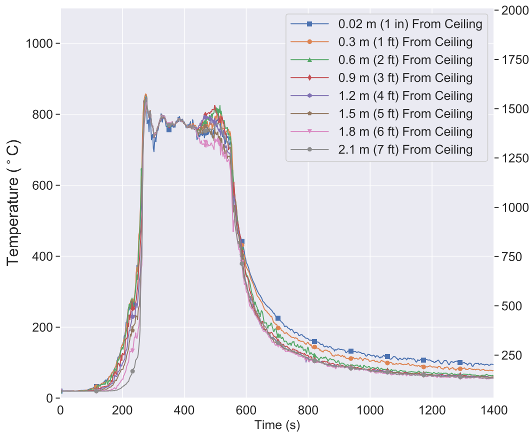
(e) Living Room Temperature



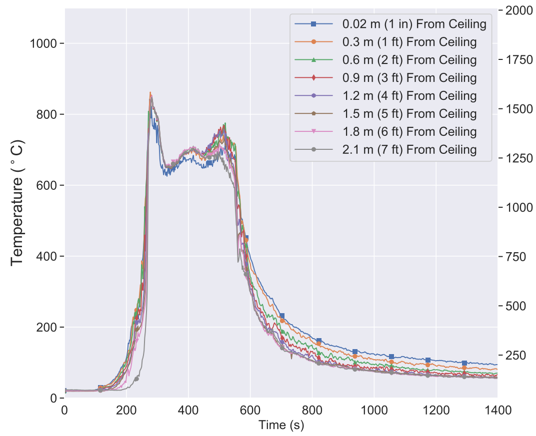
(f) Den Temperature

Figure 5.18: Experiment 3,front door, bedroom 3 door and window open, temperature time histories for family room and other first floor rooms.

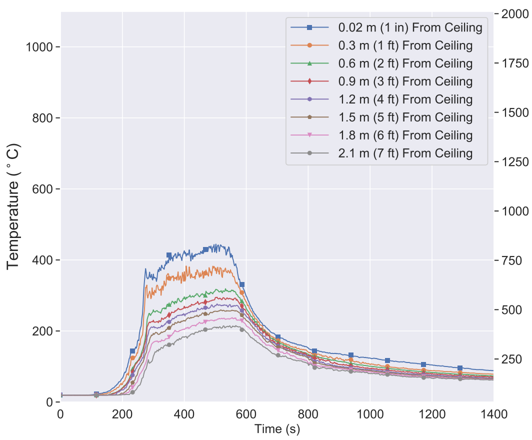
bedrooms.



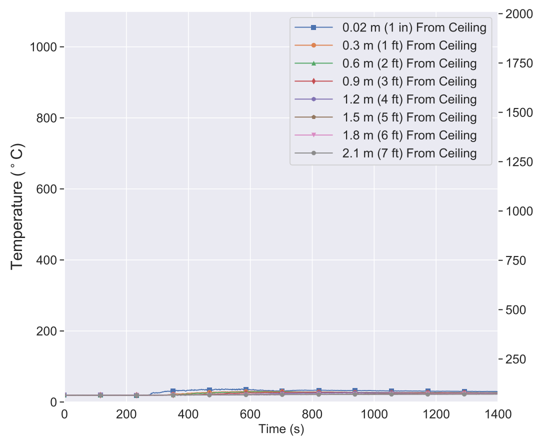
(a) Mid-Hall Temperature



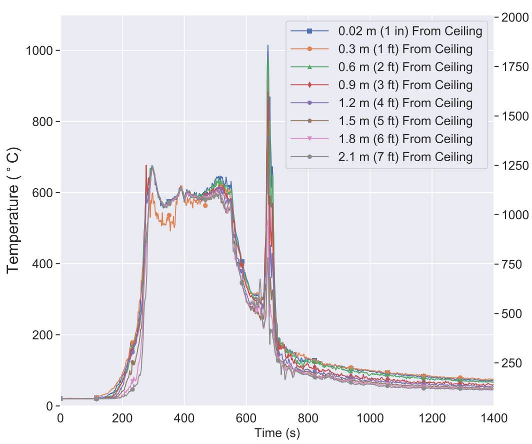
(b) End-Hall Temperature



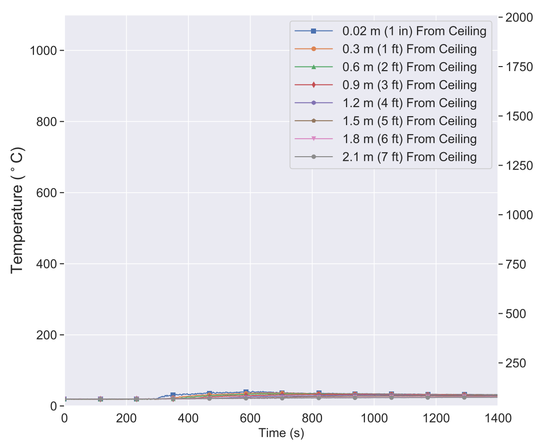
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature



(f) Bedroom 4 Temperature

Figure 5.19: Experiment 3, front door, bedroom 3 door and window open, temperature time histories for second floor hallway and bedrooms.

The velocity time history from the open front door appear in Figure 5.20. As the fire in the family room was in a rapid growth stage leading up to flashover, the door served as a uni-directional air intake vent. As the fire in the family room flashed over, the flow through the doorway reversed, and it became a uni-directional exhaust vent. As the fire in the family room stabilized to a fully developed stage, the front door transitioned into a bi-directional vent. The hot gas exhaust only flowed out of the upper portion of the doorway, while almost two-thirds of the doorway served as an air intake. This flow arrangement was maintained until fire extinguishment started and the velocities decreased.

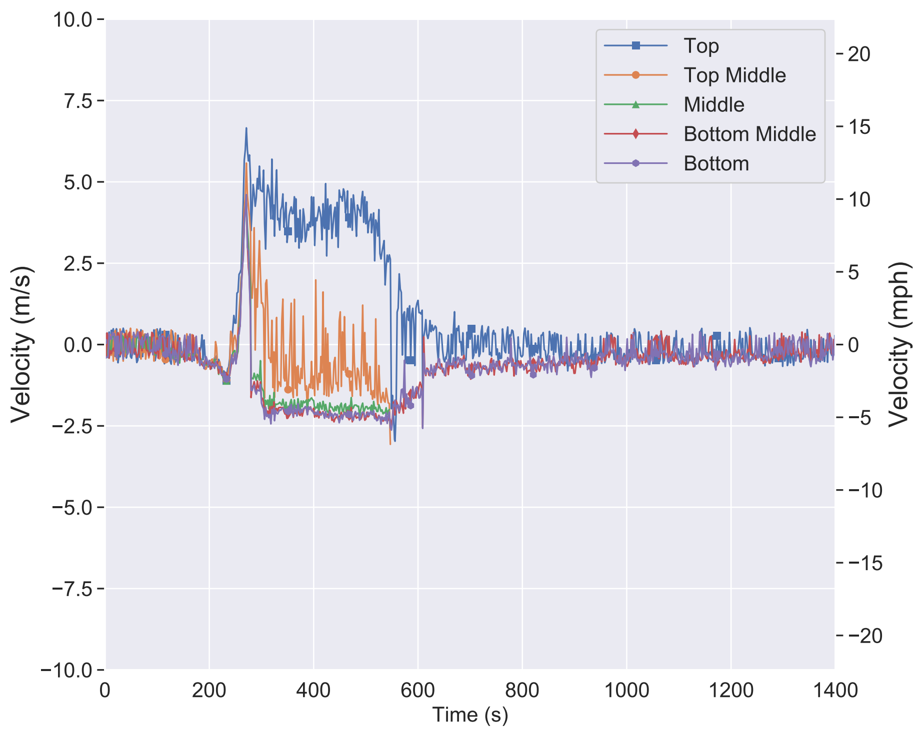


Figure 5.20: Experiment 3, front door, bedroom 3 door and window open, front door velocity versus time.

Figure 5.21 shows the flow velocities of the bedroom 3 window opening. In the first 100 s or so after ignition, there was not enough smoke developed to flow out of the window opening. Within 2 min after ignition, gases began to flow out of the top portion of the opening. As the fire growth in the family room increased, the fire gases filled the window opening. From the onset of flashover in the family room, the opening served as a uni-directional exhaust vent until the fire stabilized and spread into the bedroom. Then the bottom probe velocity started to oscillate between exhaust and intake flows, until suppression. Post-suppression of the fire inside bedroom 3 (670 to 690 s), the opening served as a bi-directional vent.

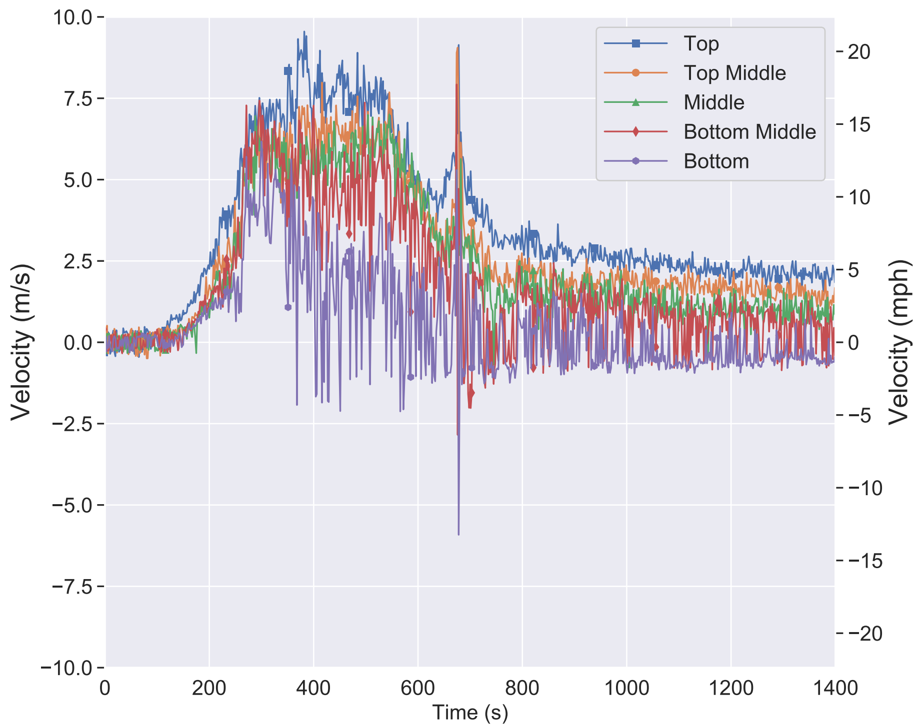
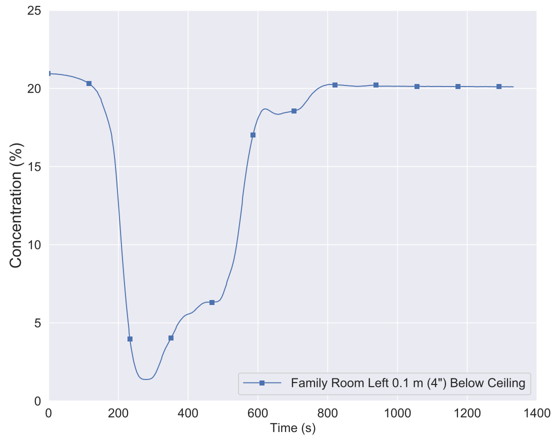


Figure 5.21: Experiment 3, front door, bedroom 3 door and window open, bedroom 3 window velocity versus time.

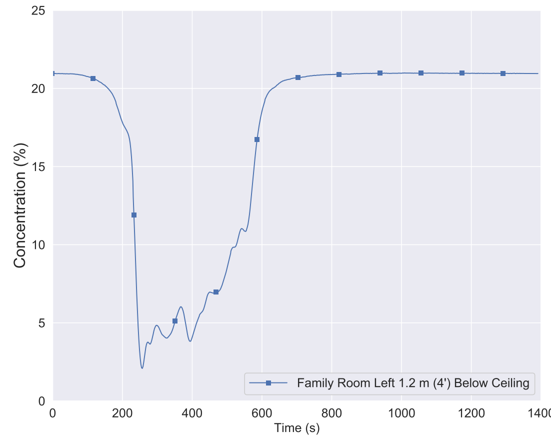
The oxygen concentrations appear in Figure 5.22. The charts shown in Figures 5.22a and 5.22b are from the sampling positions in the family room, located 0.1 m (4 in) and 1.2 m (4 ft) below the ceiling, respectively. As the flames extended to the ceiling, the oxygen concentrations decreased below 5%. The oxygen concentrations at these positions remained below 5% post-flashover for at least 100 s. The oxygen concentrations increased to approximately 7% as the fire went into the fully developed stage post-flashover. Once fire suppression, started the oxygen concentrations began to increase and continued until they had reached pre-fire, ambient levels.

Figures 5.22c and 5.22d are from the sampling positions in the family room, located 1.2 m (4 ft) and 0.1 m (4 in) above the floor, respectively. As the fire was approaching flashover, oxygen depleted gases were pushed over the oxygen sampling position near the front door and 1.2 m (4 ft) above the floor. The lowest oxygen concentrations at this height above the floor was approximately 5%. The oxygen concentrations near the floor in the family room (see Figure 5.12d) also decreased to levels between 5% and 14% while the fire was in the post-flashover fully developed stage. The oscillations are believed to be the result of air flowing along the floor from the front door into the fire room. Also, in the same graph the oxygen concentration measured near the floor just inside the front door remained above 20% for the duration of the experiment.

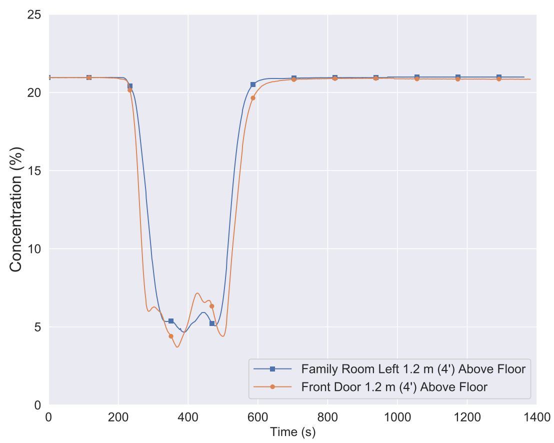
With the front door as a bi-directional vent and bedroom window opening serving mainly as an exhaust vent, the hot gas layer did not fill the lower level of the structure as thoroughly as it did in the previous experiments as additional fresh air was admitted into the structure during most of the experiment.



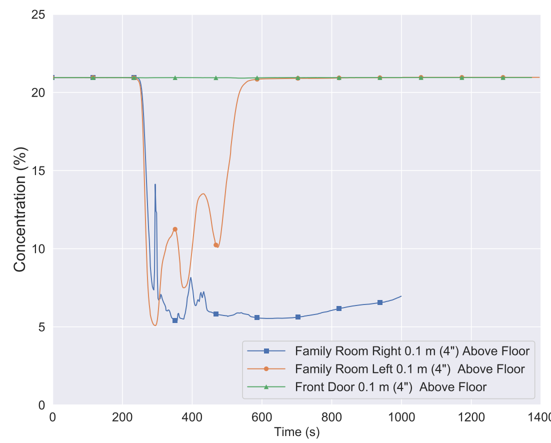
(a) Oxygen 0.1 m Below Ceiling



(b) Oxygen 1.2 m Below Ceiling



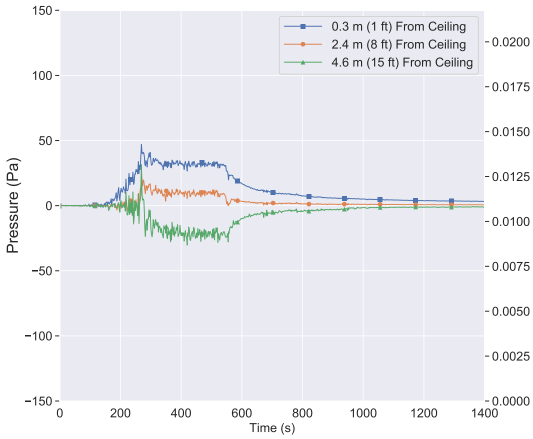
(c) Oxygen 1.2 m Above Floor



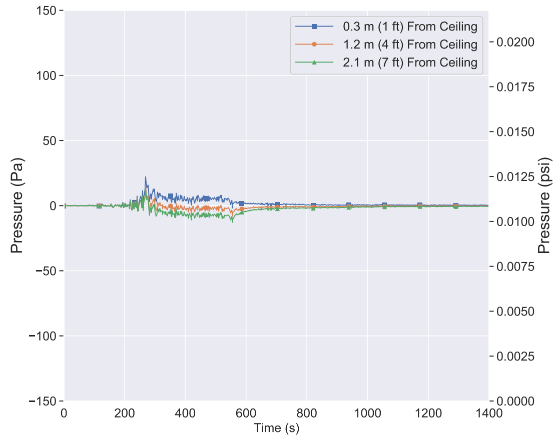
(d) Oxygen 0.1 m Above Floor

Figure 5.22: Experiment 3, front door, bedroom 3 door and window open, oxygen concentrations versus time.

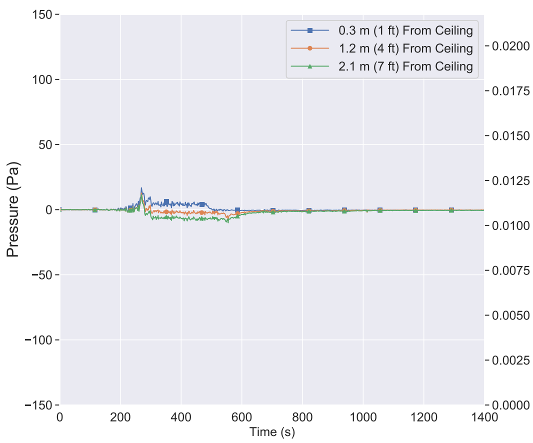
Figure 5.23 shows the pressures from the rooms on the lower level. The open front door and bedroom window opening provided an exhaust (pressure relief) on each level of the structure. The peak pressure in the family room was less than 50 Pa. The family room pressures were also the peak pressures in the structure. The pressure gradient with the higher pressures near the ceiling and the lower pressures near the floor was more pronounced than in the previous experiments. The gas pressures increased as the gas temperatures increased (gas expansion) and decreased as the gas temperatures decreased (gas contraction). The pressure difference between the ceiling and floor and between different areas of the structure resulted in gas movement from areas of higher pressure to areas of lower pressure via flow paths. The negative pressure post-flashover in the rooms on the lower level open to the fire room allowed for air to flow from the exterior. In this experiment, the den was closed off from the fire area, so the pressure in the den did not change.



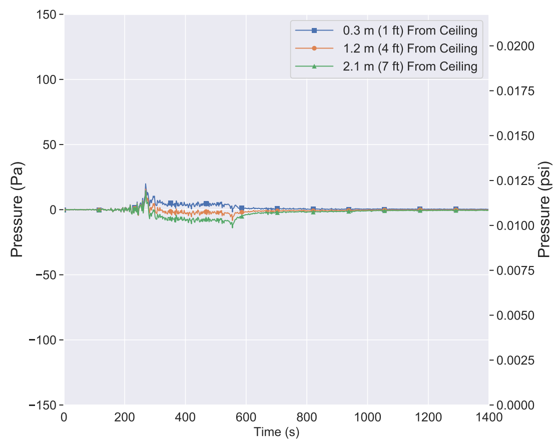
(a) Family Room Pressure



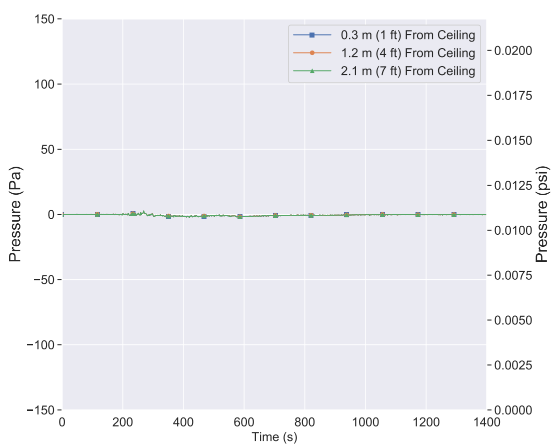
(b) Kitchen Pressure



(c) Front Door Pressure



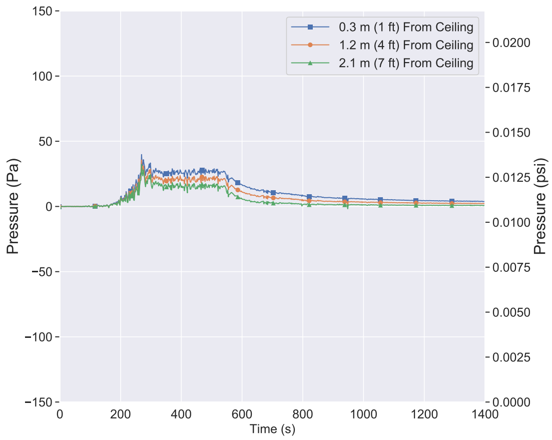
(d) Living Room Pressure



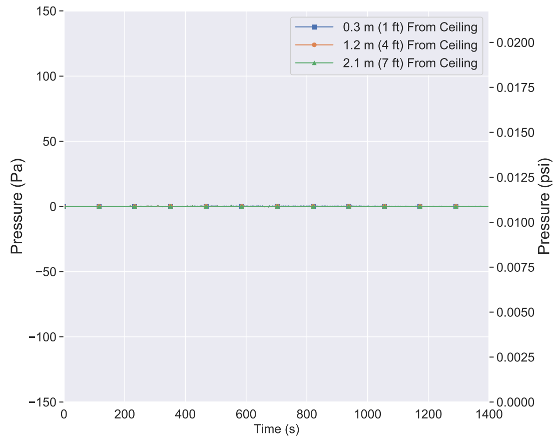
(e) Den Pressure

Figure 5.23: Experiment 3, front door, bedroom 3 door and window open, pressures in first floor rooms.

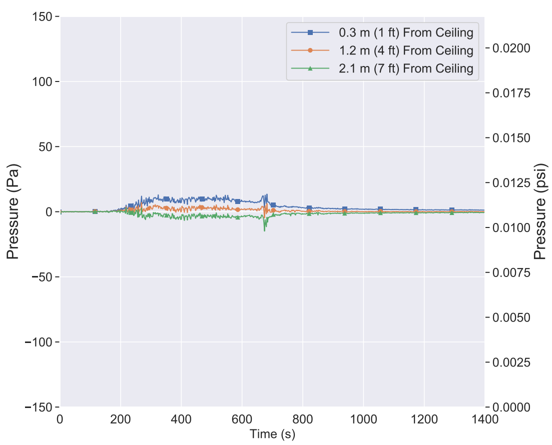
The pressures on the upper level appear in Figure 5.24. Notice how bedroom 1 was charged with positive pressure throughout the fire development and post-flashover burning period. This did not allow for efficient circulation between the gases in bedroom 1 and the hallway, which resulted in lower temperatures in bedroom 1. The pressure trends in bedroom 3 are similar to the pressures lower level open areas like the kitchen and living room. Bedrooms 2 and 4 were closed off from the fire area, which resulted in little to no pressure change within those bedrooms.



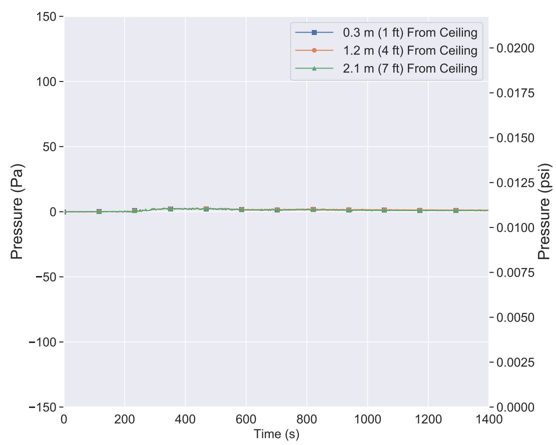
(a) Bedroom 1 Pressure



(b) Bedroom 2 Pressure



(c) Bedroom 3 Pressure



(d) Bedroom 4 Pressure

Figure 5.24: Experiment 3, front door, bedroom 3 door and window open, pressures in second floor rooms.

5.1.4 Front Door Open, Bedroom 2 and Bedroom 4 Doors and Windows Open

Experiment 4

An electric match was used to ignite the sofa. As in previous experiments, the match was positioned at the intersection of the seat cushion, the back cushion, and the right arm of the sofa. As the fire grew, a definitive thermal plume formed, and after 60 s the flames had extended above the back of the sofa and began to expose the gypsum wallboard. Within 75 s of ignition, the flames had extended vertically and smoke flowed across the ceiling in the family room. Two minutes after ignition, the flames grew to 2.4 m (7.9 ft) tall. A hot gas layer built across the family room ceiling and smoke flowed into bedrooms 2 and 4. Light gray smoke began to flow out of the open bedroom 4 window.

The fire spread along the backside of the sofa and flames extended to the side of the sofa opposite the area of origin. This resulted in a second fire plume heating the wall to the left end of the sofa at 150 s after ignition. At three minutes, the hot gas layer was approximately 1.8 m (5.9 ft) below the family room ceiling and light gray smoke flowed out of the open bedroom 4 window.

Flames spread across the seat of the first sofa ignited, and the end table became involved at 200 s. Twenty seconds later the adjacent sofa ignited and the smoke continued to build under the 1st floor ceiling. At this point, smoke filled both bedrooms 2 and 4 within 0.5 m (1.6 ft) of the floor. Black smoke was exhausting from both open bedroom windows. At 230 s, the furnished portion of the family room transitioned to flashover. After another 20 s, flames spread across the second level ceiling and entered bedroom 2. Black smoke exited the upper quarter of the open front doorway. Flames burned out of the bedroom 4 window at 260 s. As the burning in bedroom 4 continued, smoke flow from the front doorway decreased.

The family room fire was fully developed at 290 s after ignition. The flames that flowed out of the bedroom 2 window increased in size, and the smoke flow out of the bedroom 4 window also increased. At five minutes after ignition, little to no smoke flowed out the open front doorway, and a glow could be seen near the top of the doorway. The fire in the family room continued to burn, and the flows out of the bedroom 2 and 4 windows were steady.

The flames from the open bedroom 4 window decreased at 330 s, while the fire in the family room continued to burn. There was no change to the full exhaust smoke flow exiting the bedroom 2 window. After six minutes, there were increased amounts of smoke in bedroom 3, the closed bedroom. Burning continued in the family room and bedroom 4, 7 min after ignition. A glow from the fire could be seen in the bedroom 2 window. By 470 s, the fire in the family room decreased in size and flames were still exiting the bedroom 4 window, while both flames and smoke exited the bedroom 2 window. The open front doorway served as an air intake. At 8 min after ignition, suppression was started with simultaneous hose streams through the front door and into the bedroom 2 window. After 20 s, a hose stream was directed into bedroom 4. The timeline for this experiment is shown in Table 5.5.

Table 5.5: Timeline for Experiment 4, Family Room Fire with Front Door and Bedroom 2 and 4 Windows Open

Time (s)	Event
0	Ignition on right side of sofa
60	Flames have extended past the top of the back of the sofa, gypsum board exposed to flame
75	Flames have extended vertically, smoke flowing across ceiling in family room
120	Flames have grown to 2.4 m tall, HGL building across family room ceiling, smoke flowed into bedroom 2 and 4, light gray smoke flowing out of the bedroom 4 window
150	Fire spreads along the back side of the sofa, flames extend to the side of the sofa opposite the area of origin, resulting in two plumes
180	HGL is approximately 1.8 m below the family room ceiling, light gray smoke flowing out of bedroom 4 window
200	Flames spread across the seat area of first sofa ignited, end table involved
220	Adjacent sofa ignites, smoke fills both bedroom 2 and 4 within 0.5 m of the floor, black smoke exhausting from both open bedroom windows
230	Furnished portion of the family room transitioning to flashover
250	Flames spreading across second level ceiling and entering bedroom 4, black smoke exiting the upper quarter of the front doorway
260	Flames burning out of bedroom 4 window opening
270	Fire spreads across the family room, burning through bedroom 4 from hallway through the window opening, smoke flow from front doorway decreasing
290	Family room fully involved in fire, flames out of bedroom 4 window have increased in size, smoke flow out of bedroom 4 window has increased
300	Minimal smoke flow out of front doorway, glow seen near top of doorway, fire in family room continues to burn, steady flows out of bedroom 2 and 4 windows
330	Fire in family room continues to burn, flames from bedroom 4 window has decreased and smoke increased
360	Increased amount of smoke in bedroom 3, the closed bedroom
420	Burning continues in the family room and bedroom 4, glow from from fire appears in bedroom 2 window
470	Fire in family room has decreased, flames continue exiting bedroom 4 window, flames and smoke exiting bedroom 4 window
480	Start of fire suppression, simultaneous hose streams through front door and into bedroom 2 window
500	Hose stream directed into bedroom 4 window
520	Firefighters inside structure extinguishing fire in family room
540	Kitchen doors opened
570	Fire still burning in bedroom 4
685	All fires in structure extinguished

The temperatures measured by the thermocouple array positioned in the center of the family room, the array closest to the point of ignition, appear in Figure 5.25. The temperatures show the build up of the hot gas layer from the ceiling down to the floor in the first 250 s after ignition. Seconds later the temperatures in the area of the thermocouple array exceeded 1000 °C (1832 °F). The peak temperatures in the family room remained above 600 °C (1112 °F) for about 4 min. Fire suppression in the family room began at 480 s after ignition.

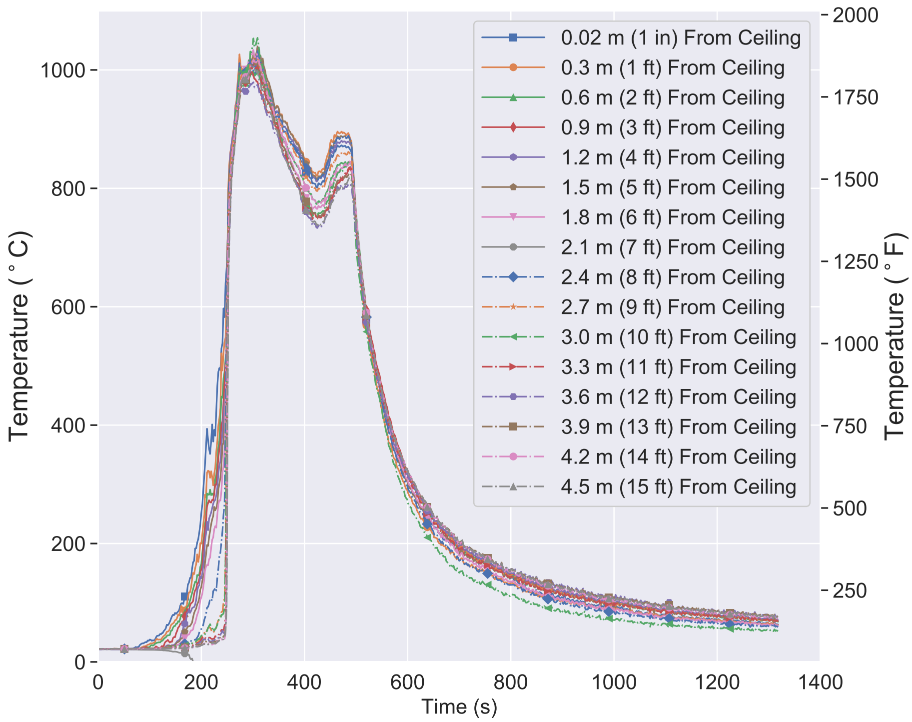


Figure 5.25: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, family room center temperatures versus time.

Figure 5.26 shows the temperatures from the front doorway during Experiment 4. As the fire in the family room was growing rapidly, the temperatures at the front door opening remained constant. Once flashover was achieved in the family room, the temperatures in the upper third of the doorway increased rapidly. As the fire continued to burn, the thermocouples in the lower two-thirds of the doorway increased to a peak temperature of 55 °C (131 °F). This increase may have been as a result of radiant heat transfer from the fire inside the structure because the lower portion of the door was serving as an air intake, and not an exhaust.

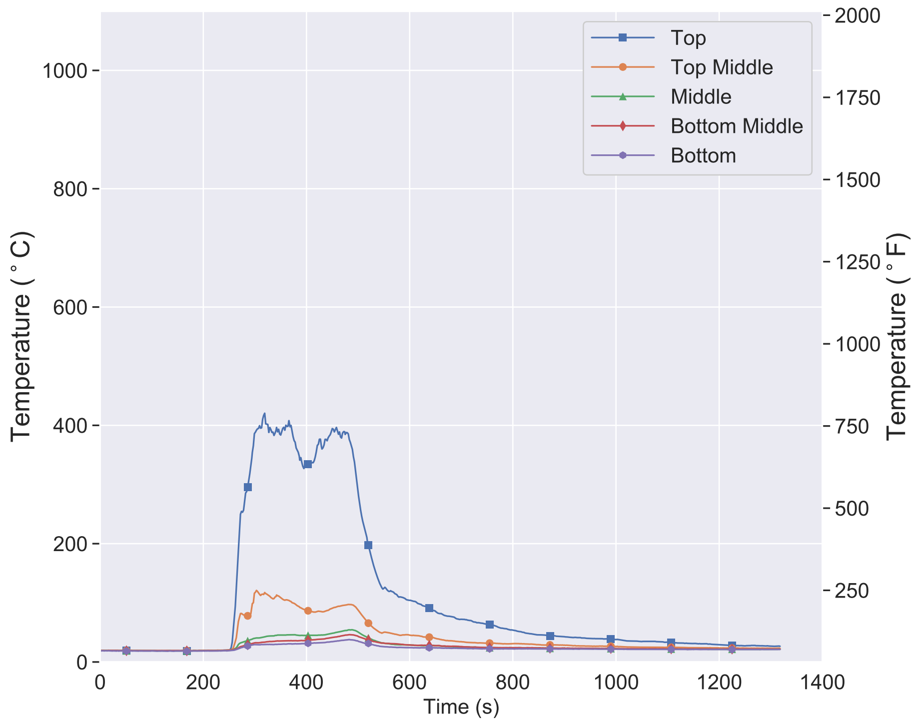


Figure 5.26: Experiment 4, Front door, bedroom 2 and bedroom 4 doors and windows open, front door temperatures versus time.

The window opening temperatures for bedroom 2 and bedroom 4 appear in Figure 5.27 and Figure 5.28. The temperatures in both window openings increased as the fire grew. The peak temperatures in the bedroom 2 window opening exceeded 600 °C (1112 °F) just prior to fire suppression. The peak temperatures in the bedroom 4 window exceeded 800 °C (1472 °F). The initial temperature increase and decrease in the window openings trended with the increase and decrease in the fire in the family room. However, as the fires in each of the bedrooms increased, the temperatures at the window openings increased independently of the temperatures from the fire in the family room. Temperatures were increasing until affected by fire suppression.

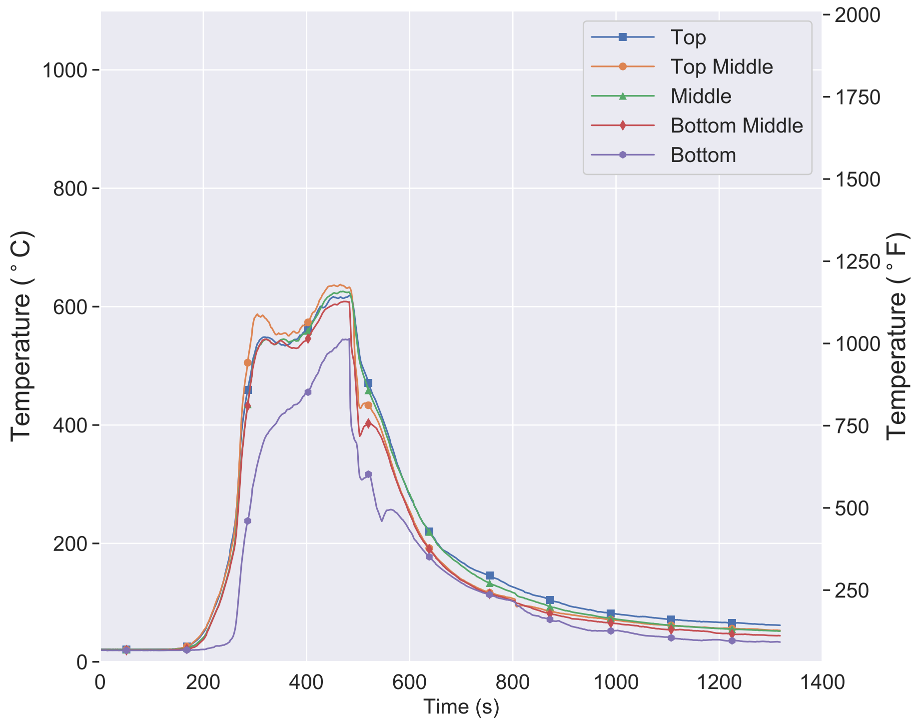


Figure 5.27: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, bedroom 2 window temperatures versus time.

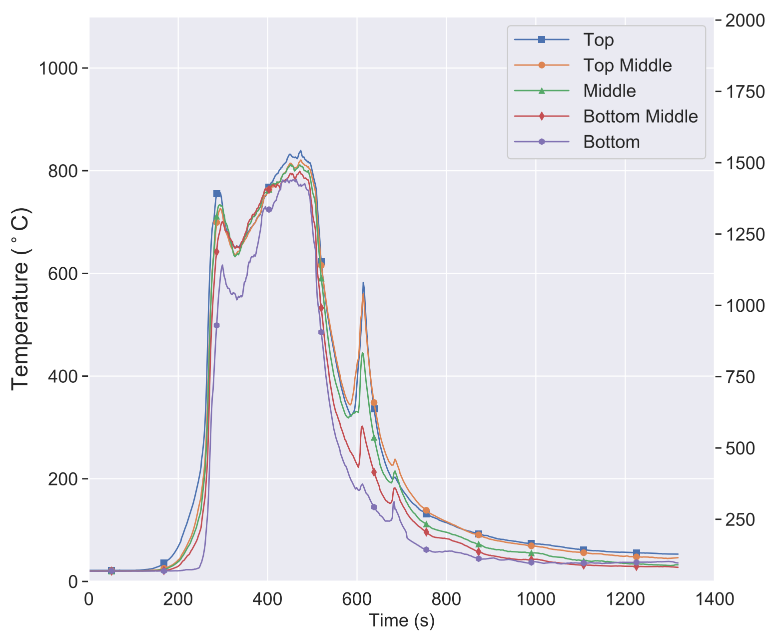
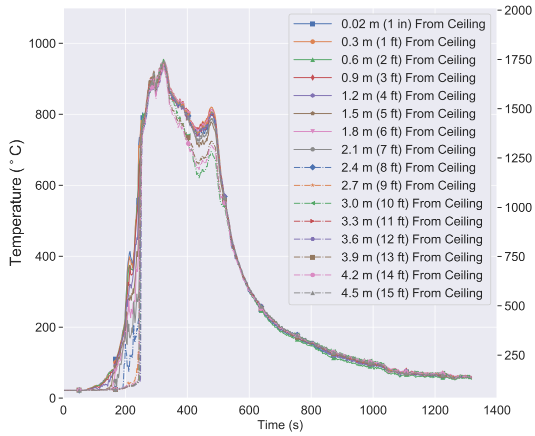
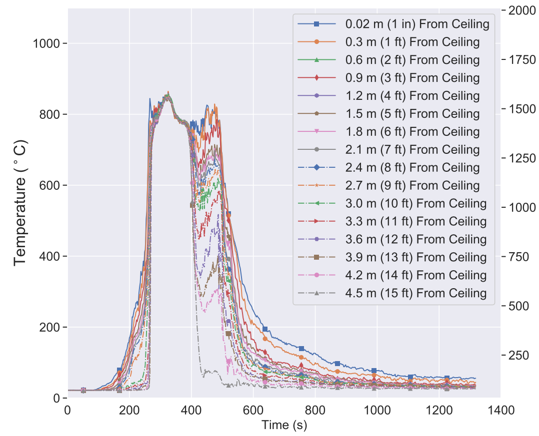


Figure 5.28: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, bedroom 4 window temperatures versus time.

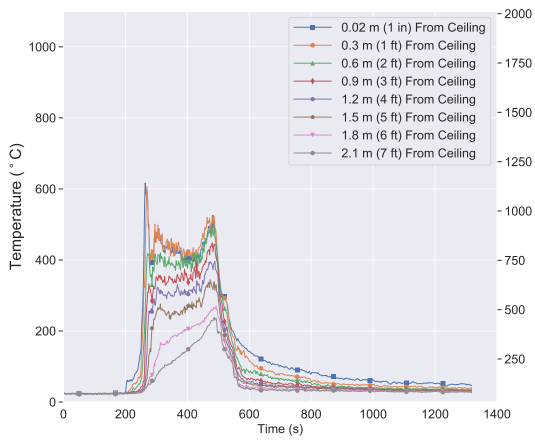
Figure 5.29 contains six graphs with the temperatures from the thermocouples arrays that were located in the areas adjacent to the fire area on the lower level. The post-flashover temperatures in the family room exceeded 600 °C (1112 °F) until the start of suppression at 480 s after ignition. The family room corner and foyer arrays were both 4.88 m (16 ft) high and therefore had the best agreement with the temperatures from the center of the family room. Although the temperatures in the foyer stratified approximately 400 s after ignition. The other three rooms open to the family room had 2.44 m (8 ft) ceilings. The kitchen, dining room, and living room (see Figures 5.18c, 4.13a, and 5.18e) did not transition through flashover. As in the previous experiments, the den had no temperature increase as a result of being closed off from the fire area.



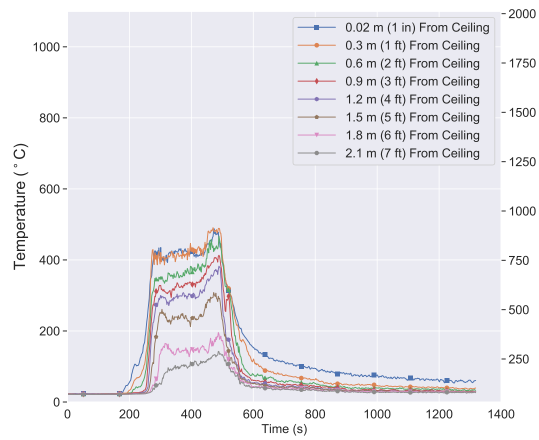
(a) Family Room Corner Temperature



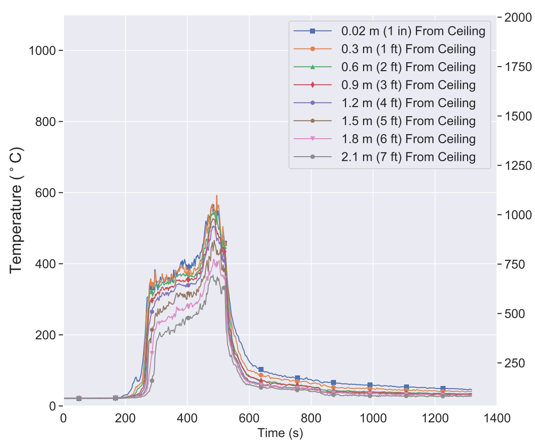
(b) Foyer Temperature



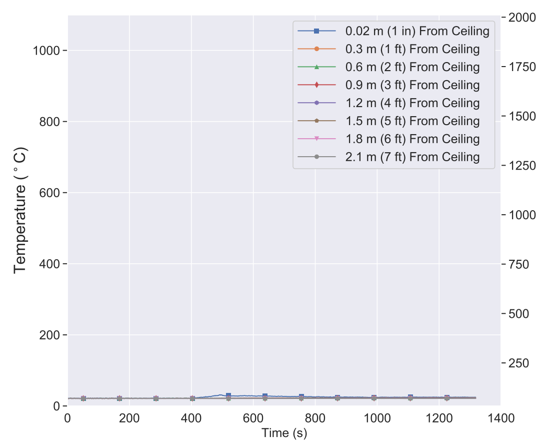
(c) Kitchen Temperature



(d) Dining Room Temperature



(e) Living Room Temperature

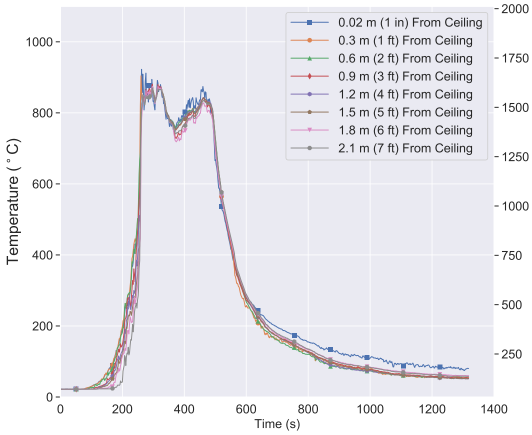


(f) Den Temperature

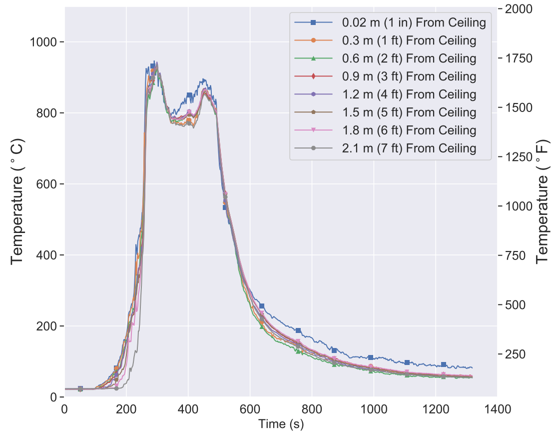
Figure 5.29: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, temperature time histories for family room and other first floor rooms.

Figure 5.30 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedrooms 1, 2, and 4 were open to the fire area from the beginning of the experiment. The graphs from the two thermocouple arrays in the hall (see Figures 5.30a and 5.30b) and the temperature graphs from bedrooms 2 and 4 (see Figures 5.30d and 5.30f) all exhibited flashover fire conditions. These arrays were in the direct exhaust flow of the hot gases as they flowed from the family room into bedrooms 2 and 4 or the foyer and then down toward the open front door. The temperatures in bedroom 1 (see Figure 5.30c) were less the other areas open to the fire room and did not approach flashover conditions. Bedroom 1 was not in the main exhaust portion of the fire flow paths and therefore had lower temperatures than the arrays that were between the fire exhaust and an exhaust vent.

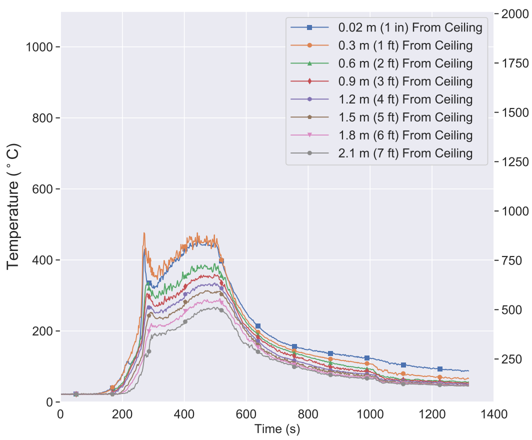
The hollow-core interior door to bedroom 3 was closed at the beginning of Experiment 4. The temperatures in bedroom 3 started to increase as the fire in the family room transitioned to flashover, as shown in Figure 5.30e. The temperatures in bedroom 3 near the ceiling peaked at approximately 450 °C (842 °F) at the start of fire suppression (t=480 s). The peak temperature 0.3 m (1 ft) above the floor was 230 °C (446 °F). After the experiment, the door was found to be burned away. However, there was no evidence of the spread of fire into the bedroom.



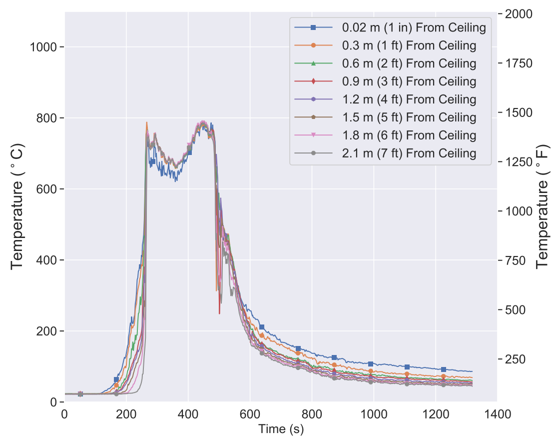
(a) Mid-Hall Temperature



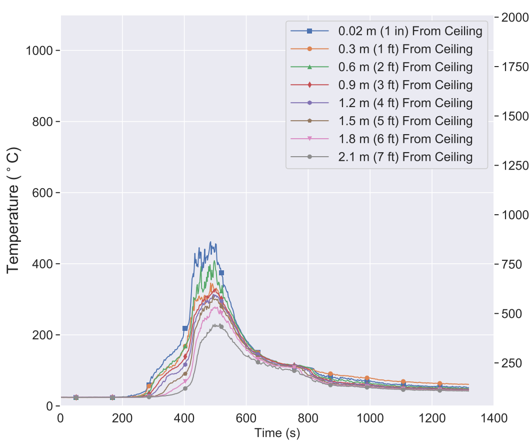
(b) End-Hall Temperature



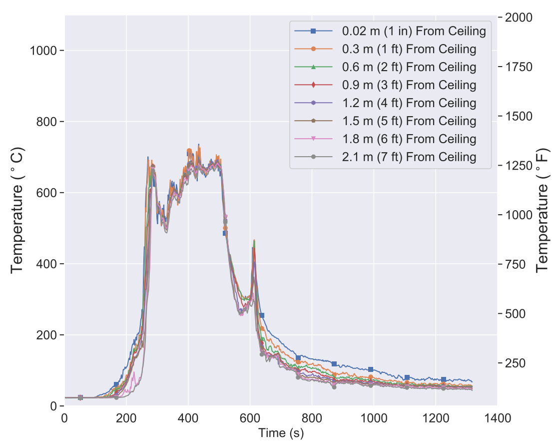
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature



(f) Bedroom 4 Temperature

Figure 5.30: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, temperature time histories for second floor hallway and bedrooms.

The velocities measured in the open front door appear in Figure 5.31. In a manner similar to experiment 3, as the fire in the family room was in the growth stage leading up to flashover, the front door served as a unidirectional air intake vent. As the fire in the family room flashed over, the flow through the doorway reversed and the door became a unidirectional exhaust vent for a short period of time. As the fire in the family room stabilized to a fully developed stage, the front door transitioned into a bi-directional vent. The hot gas exhaust only flowed out of the upper quarter of the doorway, while approximately three-quarters of the doorway served as an air intake. This flow arrangement was maintained until fire extinguishment started and the velocities decreased.

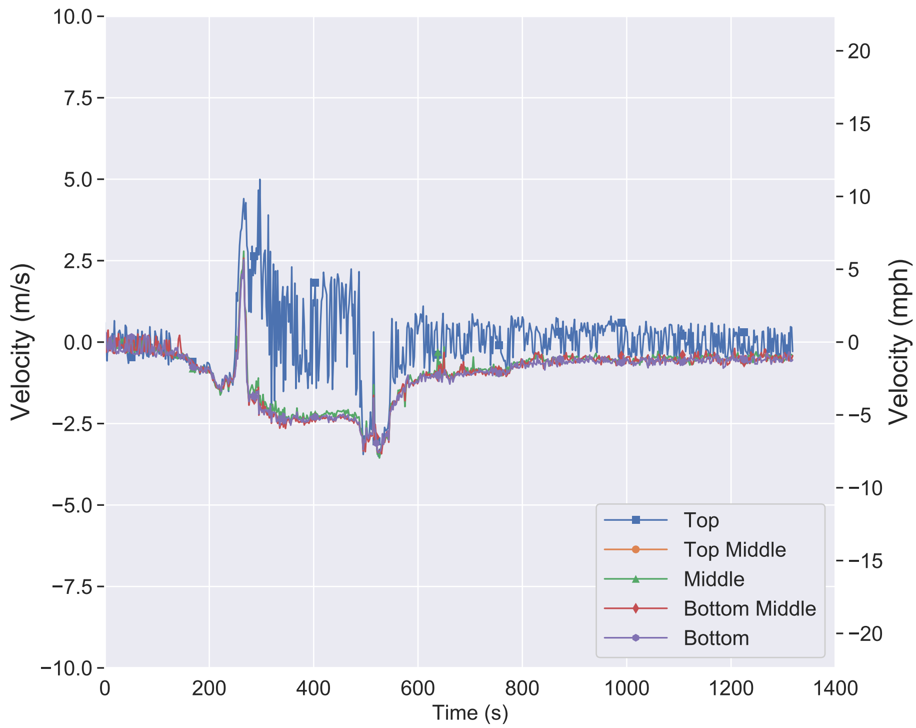


Figure 5.31: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, front door velocity versus time.

Figures 5.32 and 5.33 show the flow velocity time histories of the bedroom 2 and 4 window openings. Within 100 s after ignition, gases began to flow out of the top portion of the openings. As the fire grew in the family room, the fire gases filled the window opening. From the onset of flashover in the family room, both of the opening served as a unidirectional exhaust vents until suppression. Water that flowed into the window openings during fire suppression created the negative velocity spikes seen in the graphs.

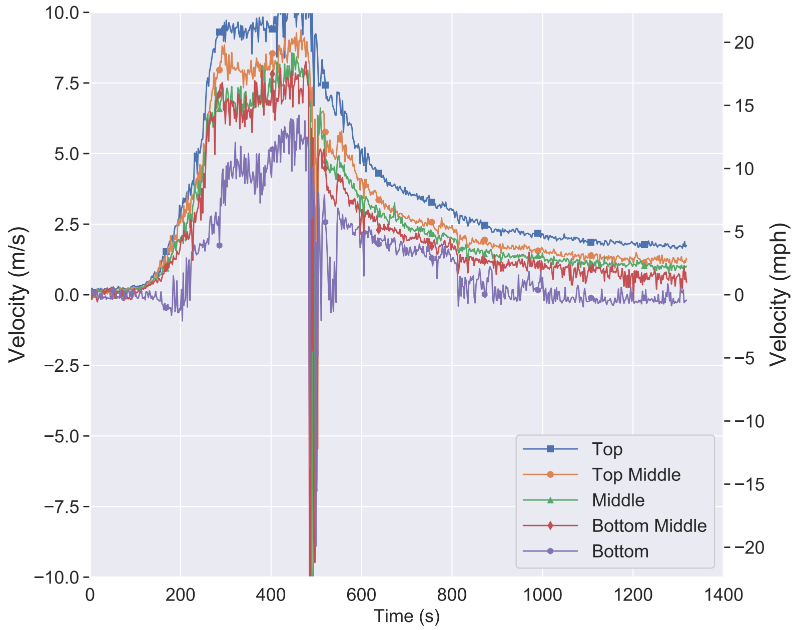
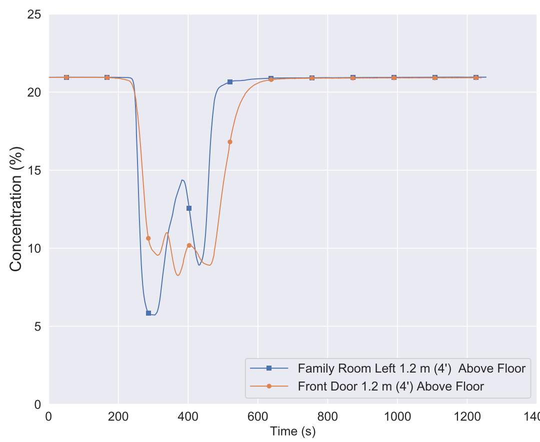


Figure 5.32: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, bedroom 2 window velocity versus time.

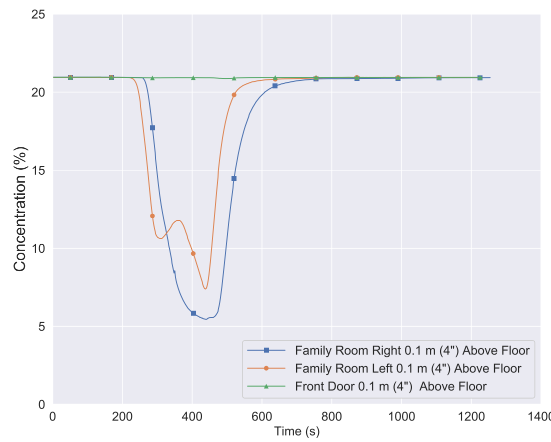
Figure 5.33: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, bedroom 4 window velocity versus time.

Figures 5.34a and 5.34b show the sampling positions in the family room and the foyer near the front door, located 1.2 m (4 ft) and 0.1 m (4 in) above the floor, respectively. Within 260 s after ignition, each of the gas sampling positions in the family room had oxygen concentrations that were decreasing. The fire in the family room had flashed over by this time, and flames were extending out of the bedroom 4 window. As the fire was approaching flashover, oxygen depleted gases were pushed over the oxygen sampling position near the front door and 1.2 m (4 ft) above the floor.

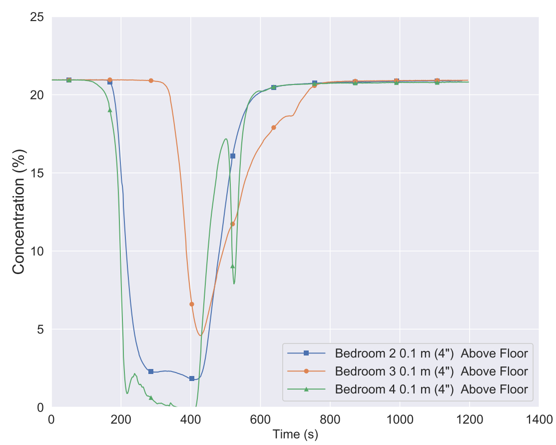
The lowest oxygen concentrations at this height above the floor was approximately 5%. The oxygen concentrations near the floor in the family room (see Figure 5.12d) also decreased to levels between 5% and 14% while the fire was in the post-flashover fully developed stage. The oscillations are believed to be the result of air flowing along the floor from the front door into the fire room. Also in the same graph, the oxygen concentration measured near the floor just inside the front door remained above 20% for the duration of the experiment. With the front door as a bi-directional vent and bedroom window opening serving mainly as an exhaust vent, the hot gas layer did not fill the lower level of the structure as thoroughly as it did in the previous experiments as additional fresh air was admitted into the structure during most of the experiment.



(a) Oxygen 1.2 m Above Floor



(b) Oxygen 0.1 m Above Floor

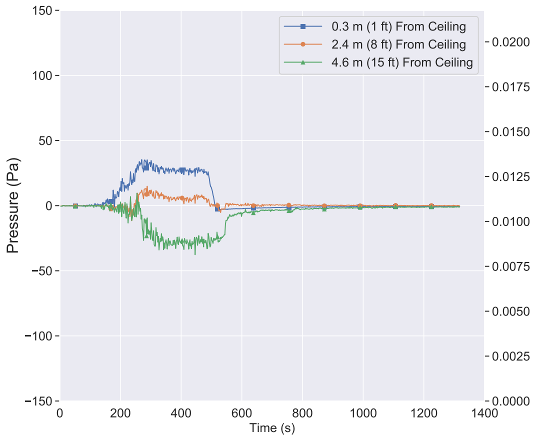


(c) Bedroom Oxygen 0.1 m Above Floor

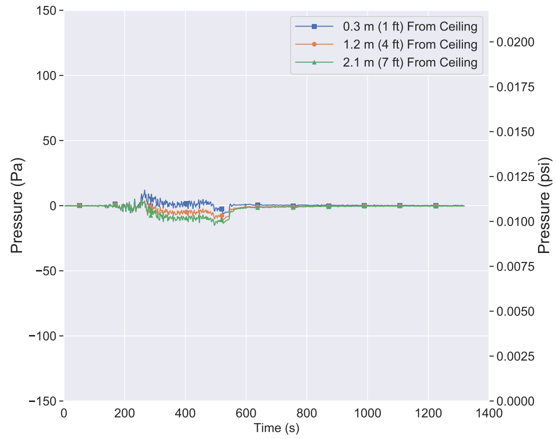
Figure 5.34: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, oxygen concentrations versus time.

Figure 5.35 shows the pressures from the rooms on the lower level. The open front door and bedroom window openings provided an exhaust (pressure relief) on each level of the structure.

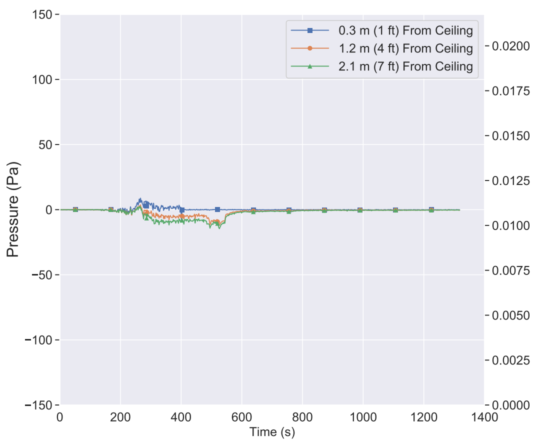
The peak pressure in the family room near the ceiling was approximately 35 Pa. This pressure was also the peak pressure in the structure. The pressure gradient with the positive pressures near the ceilings and the negative pressures near the floor was evident in all of the rooms open to the fire room on the lower level of the structure. The negative pressure provided a means for the higher pressure air entering the open front door to flow to these rooms. In this experiment, the den was closed off from the fire area so the pressure in the den did not change.



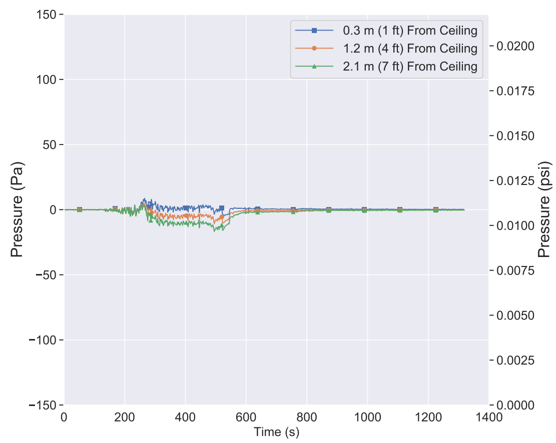
(a) Family Room Pressure



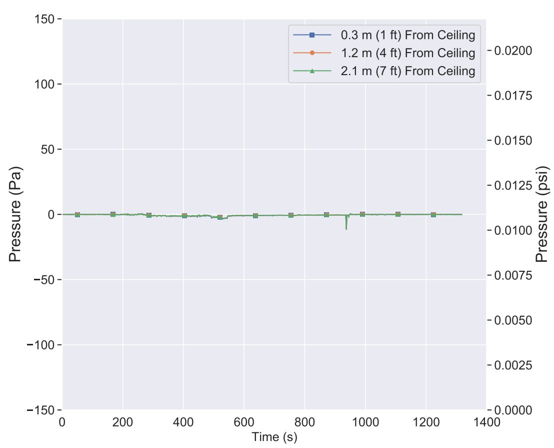
(b) Kitchen Pressure



(c) Front Door Pressure



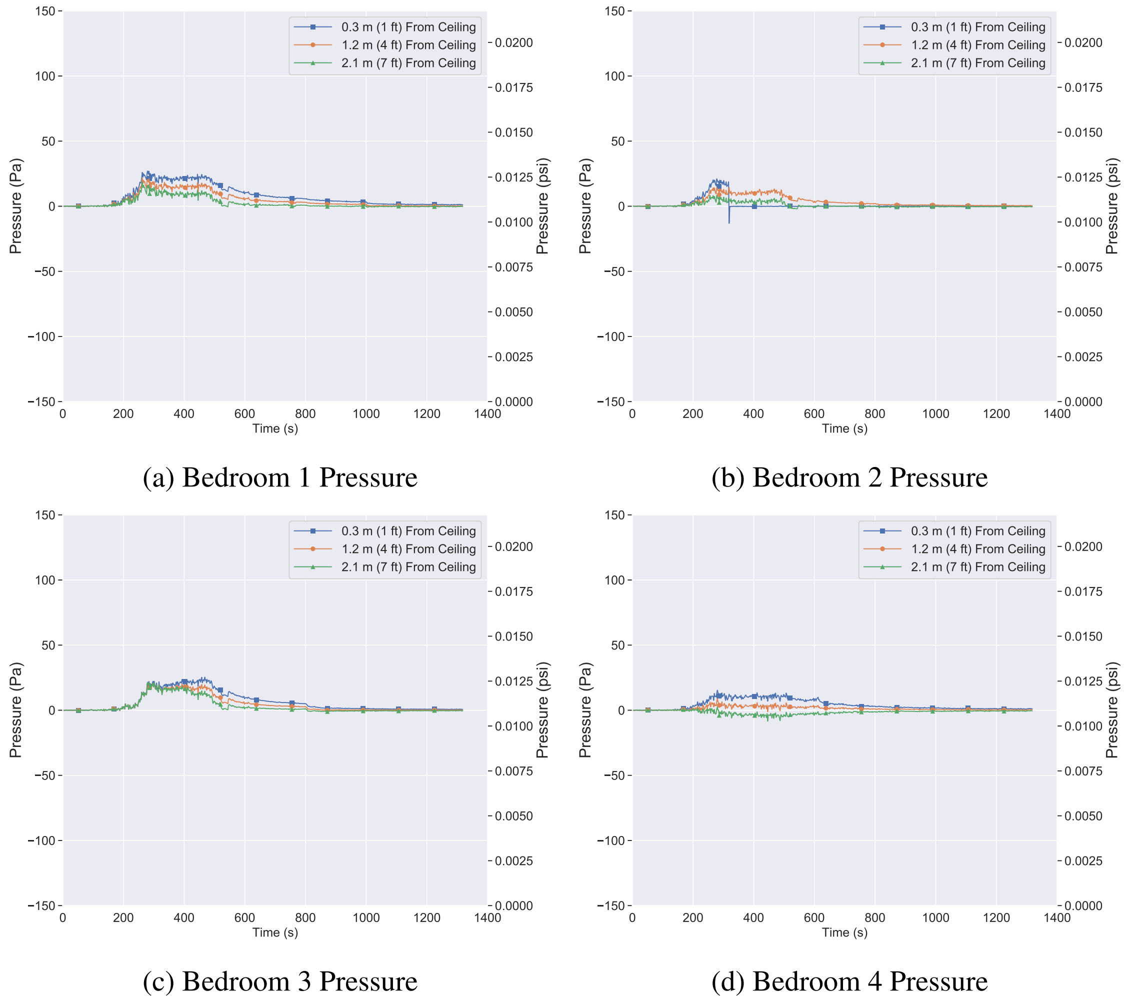
(d) Living Room Pressure



(e) Den Pressure

Figure 5.35: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, pressures in first floor rooms.

The pressures on the upper level appear in Figure 5.36. Bedroom 1 and 3 were charged with positive pressure throughout the fire development and post-flashover burning period. The pressure trends in bedrooms 2 and 4 displayed some differences. Bedroom 4 had positive pressures in the upper portion on the room and a slight negative pressure near the floor. Bedroom 2 had a positive pressure profile from the ceiling down to the floor. The window opening in bedroom 4 was twice as large as the window opening in bedroom 2. As a result, bedroom 2 was able to maintain a positive pressure throughout its elevation.



(a) Bedroom 1 Pressure

(b) Bedroom 2 Pressure

(c) Bedroom 3 Pressure

(d) Bedroom 4 Pressure

Figure 5.36: Experiment 4, front door, bedroom 2 and bedroom 4 doors and windows open, pressures in second floor rooms.

5.1.5 Front Door and Family Room Window Open

Experiment 8

An electric match was used to ignite the sofa. As in previous experiments, the match was positioned at the intersection of the seat cushion, the back cushion, and the right arm of the sofa. As the fire grew, a definitive thermal plume formed, and within two minutes of ignition the flames had extended above the back of the sofa and began to expose the gypsum wallboard. Compared to the previous four family room experiments, in this experiment the vertical flame extension to the top of the sofa back took more than twice the time to expose the wall to the flame. Smoke began to flow across the ceiling in the family room at 150 s, and by 200 s there was a hot gas layer approximately 1.2 m (3.9 ft) thick building across the family room ceiling.

Four minutes after ignition, the fire spread, involving half of the sofa, while the smoke began to spread out under the first floor ceiling. Smoke began to flow out of the open front doorway at 255 s, and 5 s later, light smoke started to flow out of the open family room window. At 310 s the sofa was fully involved in fire, and black smoke exited the upper half of the open front doorway as well as the upper quarter of the open family room window.

After 330 s, the fire in the family room had spread to adjacent furnishings, and 10 s later the family room transitioned to flashover. Flames began exiting the open family room window, and the change in pressure caused the front door to close. After 10 s more, the fire in the family room appeared to decrease in size, and the front door was re-opened by a firefighter at 370 s.

Smoke exited the upper one-third of the open front doorway and the upper half of the open family room window at 7 min after ignition. By 8 min, the fire area was limited to the furnished area of the family room near the open window. Nine minutes after ignition, the fire in the family room had decreased in size. Flames were no longer flowing out of the open family room window. Fire suppression was started with a hose stream through the open family room window at 570 s. A minute later the kitchen door was opened, and within 15 s, firefighters were extinguishing the hot spots in the family room. Table 5.6 provides a timeline of events.

Table 5.6: Timeline for Experiment 8, Family Room Fire with Front Door and Family Room Window Open

Time (s)	Event
0	Ignition on right side of sofa
120	Flames extend past the top of the back of the sofa, gypsum board exposed to flame
150	Smoke flowing across ceiling in family room
200	Hot gas layer approximately 1.2 m thick building across family room ceiling
240	Fire has spread and involves half of the sofa, smoke beginning to spread under first floor ceiling
255	Smoke flow out of front doorway starts
260	Light smoke has started to flow out of the open family room window
310	Sofa fully involved in fire, black smoke exiting upper half of front doorway, and black smoke flowing from upper quarter of open family room window
330	Fire in family room spreading to adjacent furnishings
340	Furnished portion of the family room is transitioning to flashover, flames exiting open family room window, pressure in foyer closed front door
350	Fire in family room appears to decrease in size
370	Front door re-opened by a firefighter
420	Smoke exiting from the upper third of the front doorway and the upper half of the open family room window
480	Fire area limited to furnished area of family room near open window
540	Fire in family room decreased in size, flames no longer flowing out of open family room window
570	Fire suppression started with hose stream through open family room window
630	Firefighters open kitchen door
645	Firefighters extinguishing hot spots in family room

Figure 5.37 shows the temperatures of the thermocouple array in the center of the family room. The temperatures near the ceiling began to increase approximately 150 s after ignition. With the window open next to the ignition sofa, and the open front door, the build up of heat in the family room is slower than in the previous four family room experiments. At 340 s after ignition, the temperatures near the floor began to increase rapidly as the fire transitioned to flashover. Within the next 10 s, all of the temperatures in the family room exceeded 600 °C (1112 °F). The fire only maintained this uniform, well-mixed burning environment for approximately 20 s. After that the temperatures began to decrease and stratify. This change was likely caused by the closure of the front door.

After the front door was reopened at 370 s after ignition, the fire appeared to reach a steady state burning rate and the temperatures held steady for about one minute. After this point, the fire seemed to decrease based on the amount of fuel available. This trend continued until suppression started at 570 s after ignition.

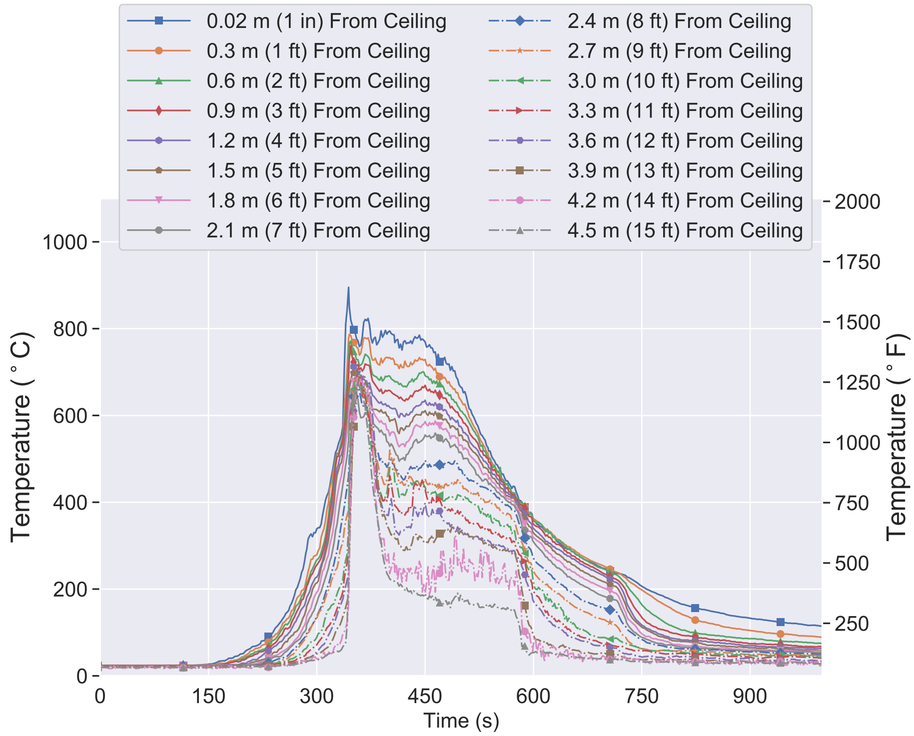


Figure 5.37: Experiment 8, front door and family room window open, family room center temperatures versus time.

The temperatures measured at the front door appear in Figure 5.38. The rapid decrease and increase in temperatures starting at 304 s after ignition shows the impact of the front being closed and then reopened. The temperatures in the upper third of the doorway show the most temperature increase. This is consistent with the flow of smoke observed out of the doorway.

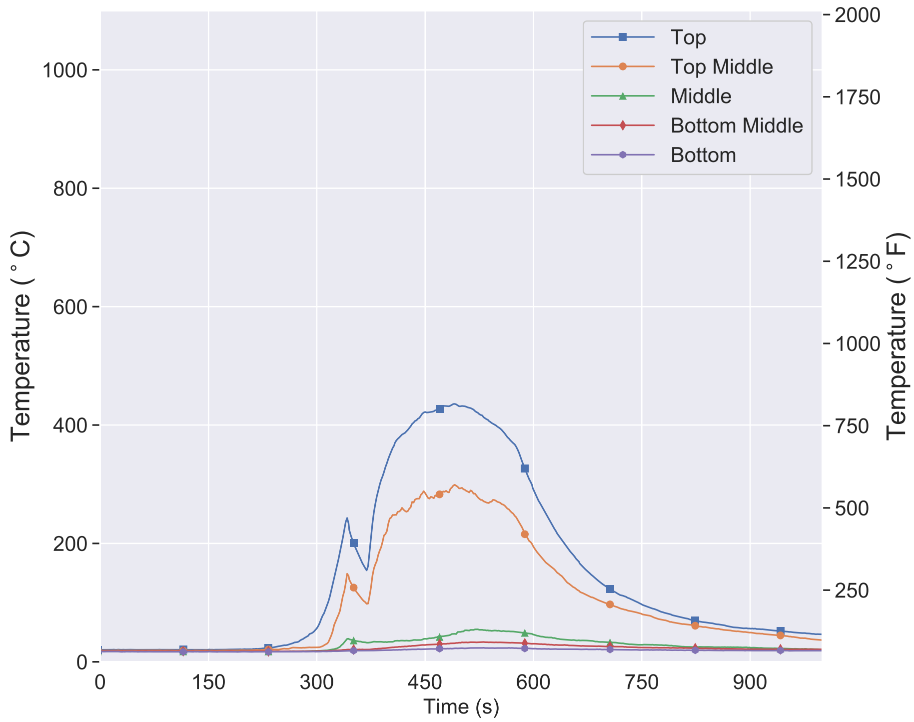
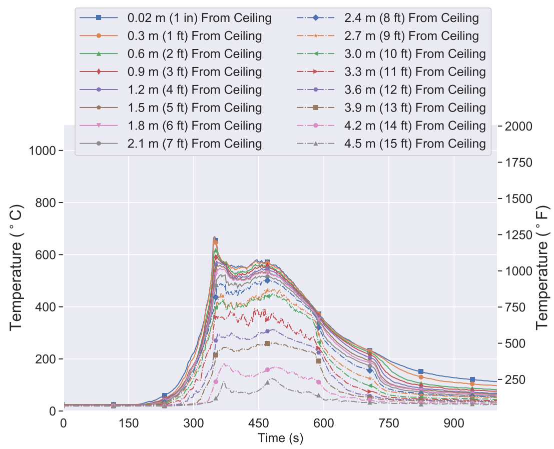


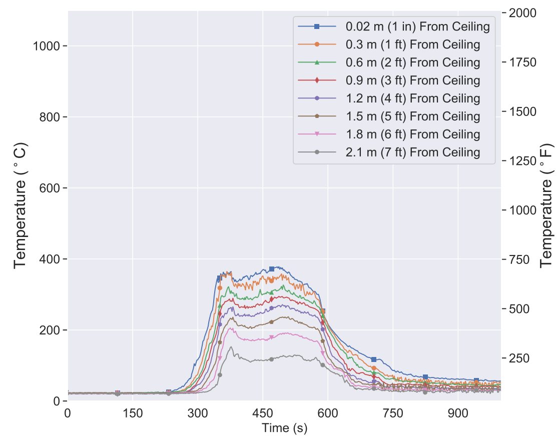
Figure 5.38: Experiment 8, front door and family room window open, front door temperatures versus time.

Figure 5.39 shows the four temperature time histories of the rooms open to the family room the lower level of the structure. The thermocouple array in the foyer extends down through the 4.88 m (16 ft) high space (see Figure 5.39a). In the foyer, temperatures 3.0 m (10 ft) below the ceiling exceeded 400 °C (752 °F) during the fully developed fire stage.

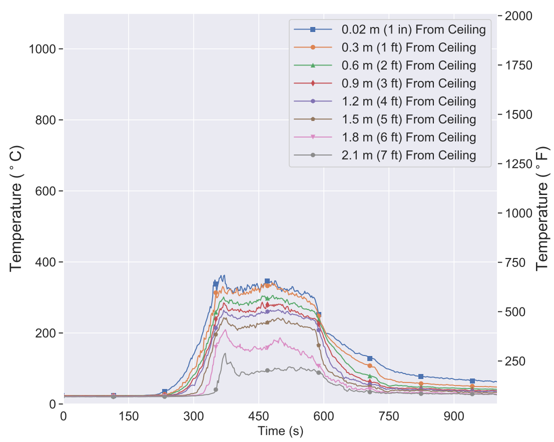
The kitchen, dining room, and living room all had 2.44 m (8 ft) ceilings. None of the temperatures in those rooms exceeded 400 °C (752 °F). The kitchen and dining room had similar temperature trends and magnitudes. The kitchen and dining room are adjacent and connected to each other by a doorway. In addition, both are open to the flow path between the fire and the front door. The living room exhibits the same trend as the kitchen and dining room. However, the peak temperatures near the ceiling were cooler and the temperatures near the floor were higher than those in the other two rooms. A graph for the temperatures in the den is also included. The den was closed and therefore its temperature changes were minor.



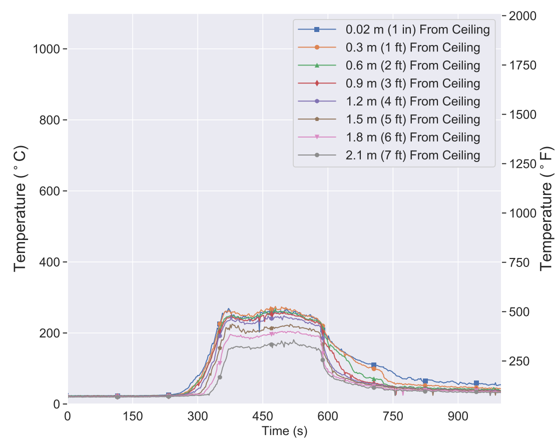
(a) Foyer Temperature



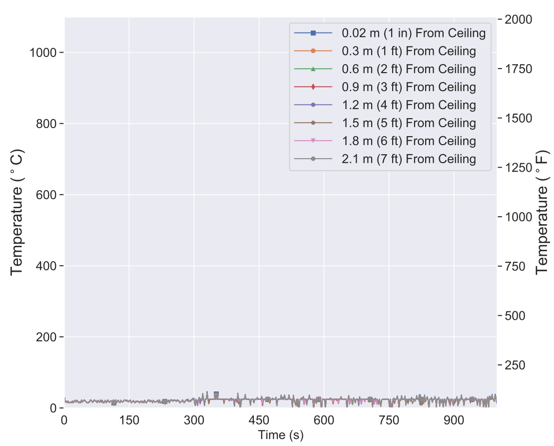
(b) Kitchen Temperature



(c) Dining Room Temperature



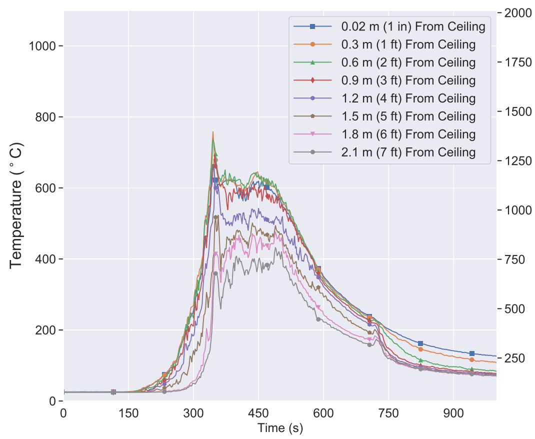
(d) Living Room Temperature



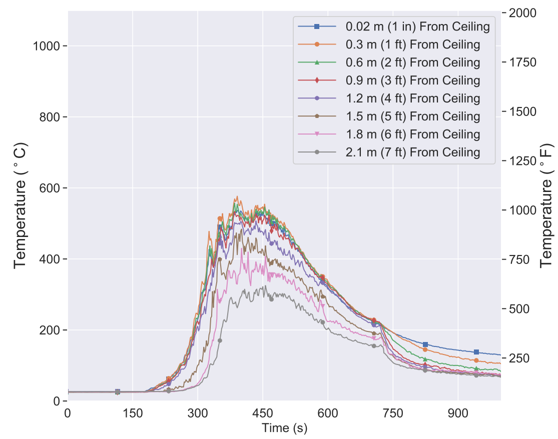
(e) Den Temperature

Figure 5.39: Experiment 8, front door and family room window open, temperature time histories for family room and other first floor rooms.

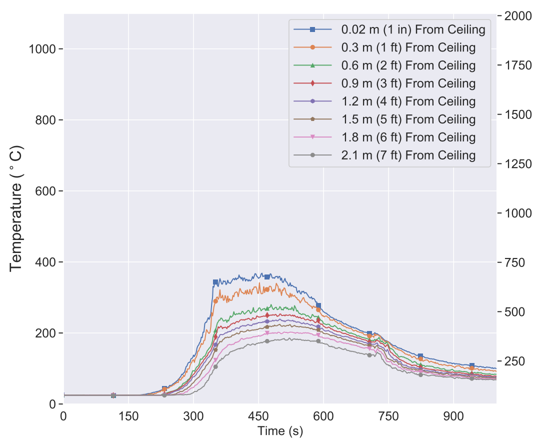
Figure 5.40 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedroom 1 were open to the fire area. The mid-hall array temperatures shown in Figure 5.40a had the most similar temperatures and treads as the temperatures in the family room. This array is also in the direct exhaust flow of the hot gases as they flowed from the family room into the foyer and down toward the open front door. As the distance from the mid-hall position increased while moving toward bedroom 1, the temperatures tended to decrease. Bedroom 1, much like the living room, is not part of the main fire flow paths and therefore had lower temperatures than the hallway arrays. Bedrooms 2, 3, and 4 were isolated from the fire area by having the doorways closed off, so there was little to no increase in temperature in the bedrooms.



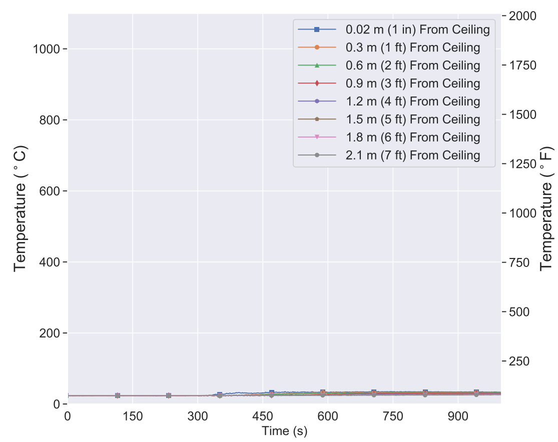
(a) Mid-Hall Temperature



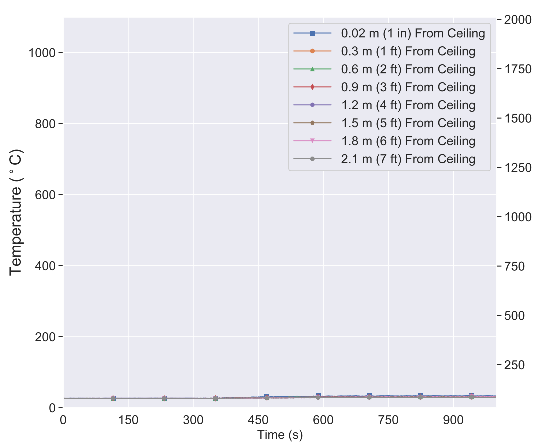
(b) End-Hall Temperature



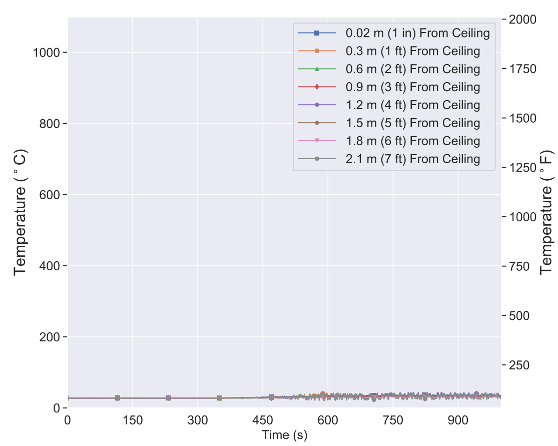
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature



(f) Bedroom 4 Temperature

Figure 5.40: Experiment 8, front door and family room window open, temperature time histories for second floor hallway and bedrooms.

The velocities measured at the front door appear in Figure 5.41. As the fire was growing, the flows out of the upper portion of the doorway increased, then the flow and pressure increase at the front door caused the front door to close, which in turn cut of the flow to the gas velocity probes. After the firefighter reopened the front door, bidirectional flows were established, correlating with the fully developed fire stage in the family room. The sharp decrease in hot gas velocities at 570 s was the result of the initial fire suppression action in the family room.

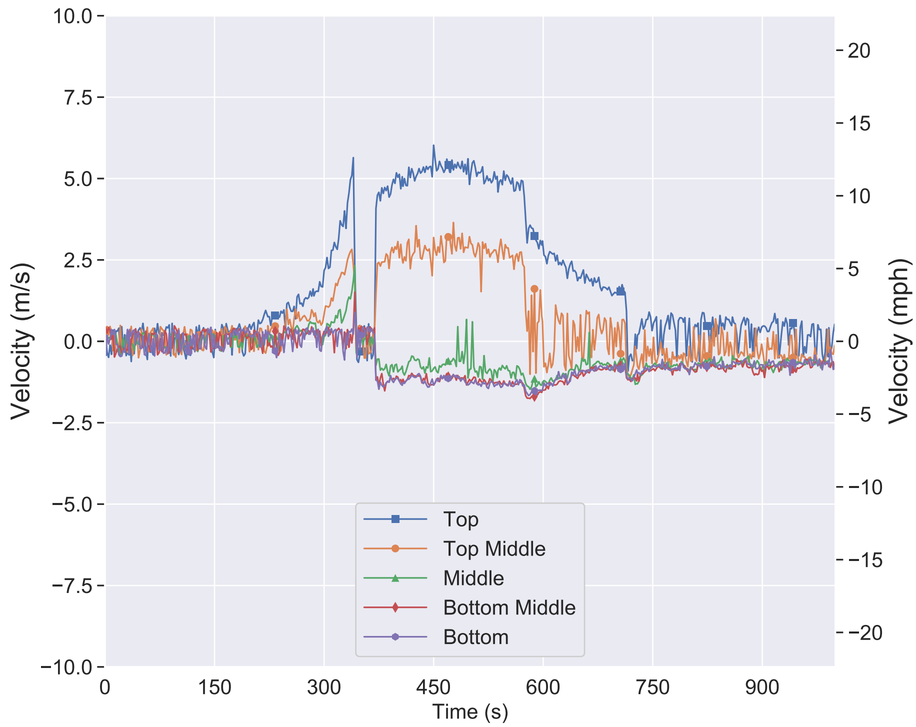


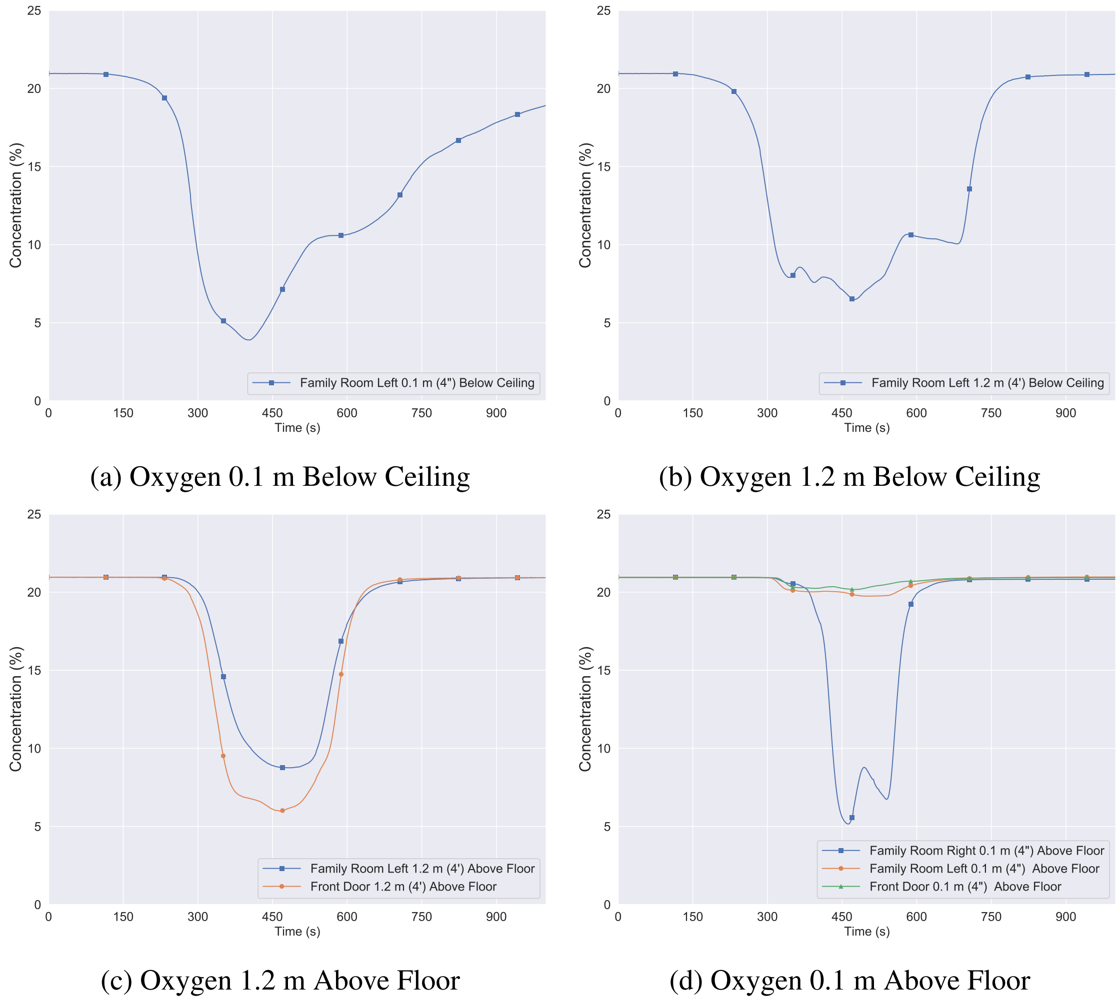
Figure 5.41: Experiment 8, front door and family room window open, front door velocity versus time.

The oxygen concentrations appear in Figure 5.42. The chart shown in Figure 5.42a shows the sampling position in the family room, located 0.1 m (4 in) below the ceiling, respectively. As the flames extended to the ceiling, the oxygen concentrations close to the ceiling decreased below 5% while the fire was in the fully developed stage. As the fire decreased in size based on fuel depletion, the oxygen concentration began to increase.

The oxygen sampling location at 1.2 m (4 ft) below the ceiling, (see Figure 5.42b) had oxygen concentration in the range of 5% to 10% in during the fire's fully developed stage. This range of values is the same for the sampling locations 1.2 m (4 ft) above the floor both in the family room and near the front door.

Figure 5.42d shows significant variations in the oxygen concentrations at different positions 0.1 m (4 in.) above the floor. The location closest to the ignition sofa had the oxygen concentration level decrease down to 5% to 10%, while the locations on the opposite end of the family room and near the front door remained near 20%.

The open front door and family room served as bidirectional vents providing for both exhaust and air intake. As a result, the hot gas layer did not fill the lower layer of the structure to the extent it had in the previous experiments with less ventilation, and as a result the oxygen concentrations remained higher than in the previous experiments.



(a) Oxygen 0.1 m Below Ceiling

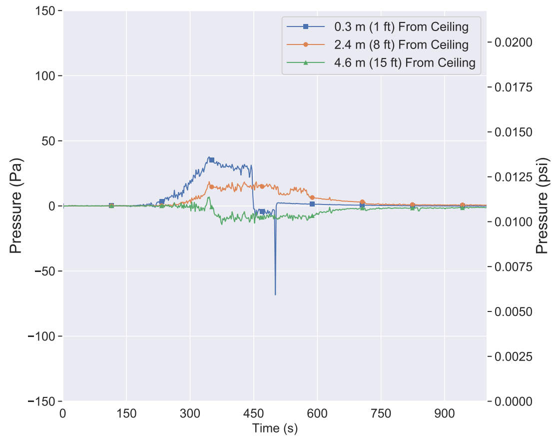
(b) Oxygen 1.2 m Below Ceiling

(c) Oxygen 1.2 m Above Floor

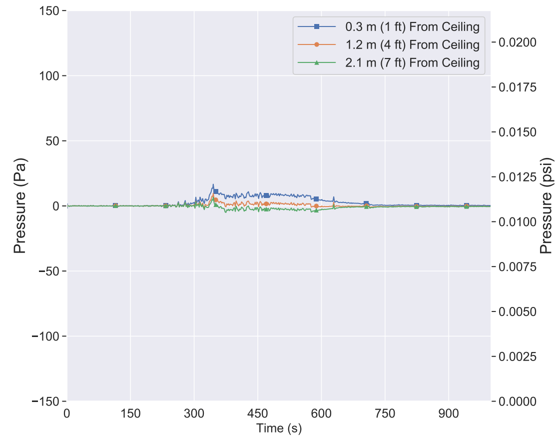
(d) Oxygen 0.1 m Above Floor

Figure 5.42: Experiment 8, front door and family room window open, oxygen concentrations versus time.

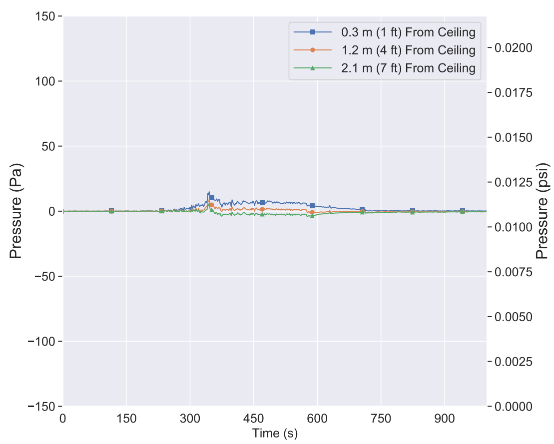
Figure 5.43 shows the pressures from the rooms on the lower level. The peak pressure in the family room was less than 50 Pa. The family room pressures were also the peak pressures in the structure. The pressure gradient with the higher pressures near the ceiling and the lower pressures near the floor was consistent in the room open to the family room. As noted before, the gas pressures increased as the gas temperatures increased (gas expansion) and decreased as the gas temperatures decreased (gas contraction). The pressure difference between the ceiling and floor and between different areas of the structure resulted in gas movement from areas of higher pressure to areas of lower pressure via flow paths. The slightly negative pressures post-flashover in the kitchen, living room, and front door positions near the floor allowed for the higher pressure outside air to flow into the structure. In this experiment, as with the other family room experiments, the den was closed off from the fire area so the pressure in the den did not change. The pressure channel closest to the ceiling failed at approximately 450 s after ignition.



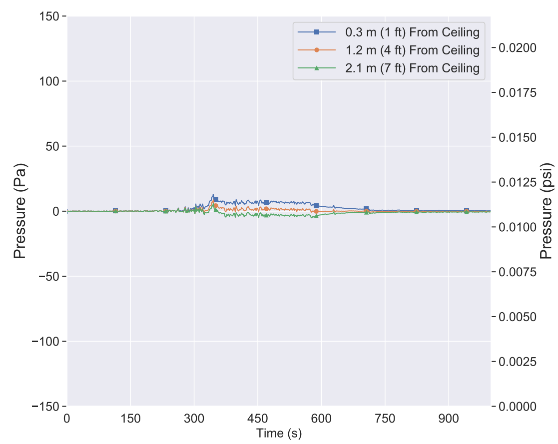
(a) Family Room Pressure



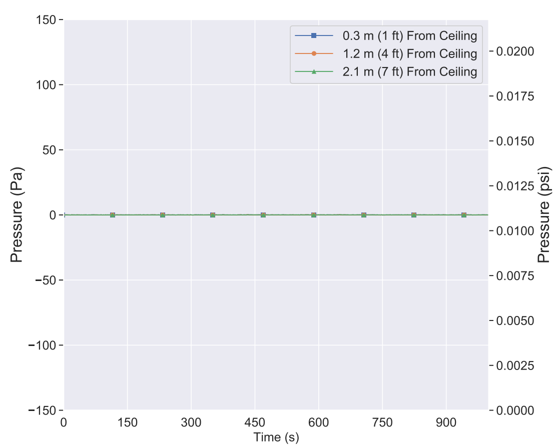
(b) Kitchen Pressure



(c) Front Door Pressure



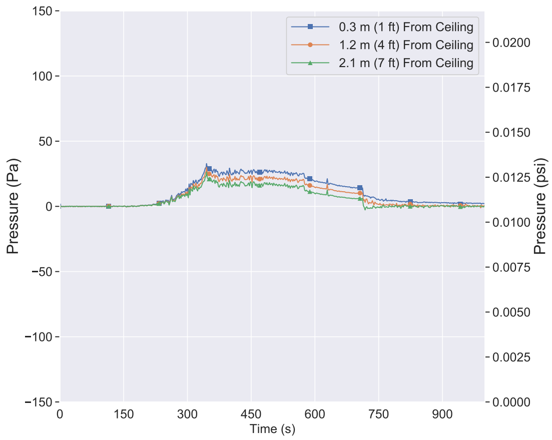
(d) Living Room Pressure



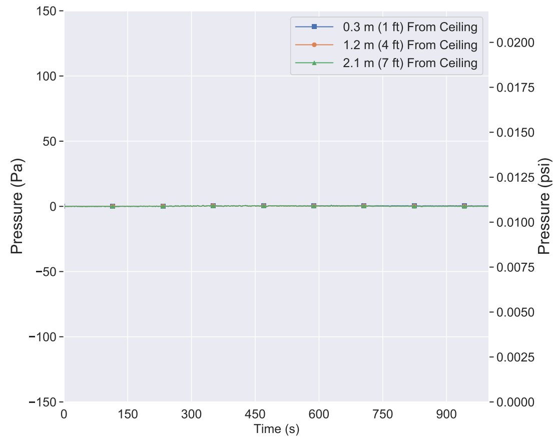
(e) Den Pressure

Figure 5.43: Experiment 8, front door and family room window open, pressures in first floor rooms.

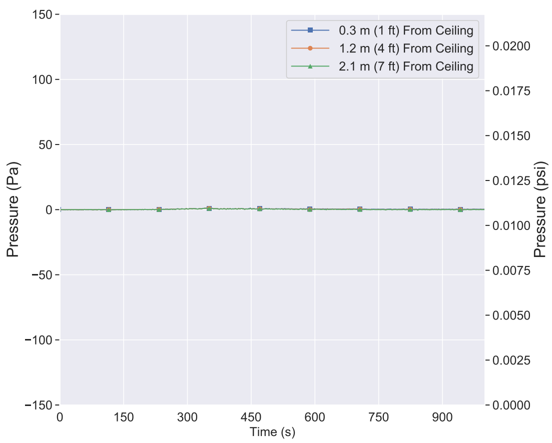
The pressures on the upper level are shown in Figure 5.44. Bedroom 1 was the only room open to the fire area. The pressure trends in bedroom 1 are similar to the pressure in the upper portion of the family room because the bedroom is positioned above the neutral plane in the structure. Bedroom 1 maintained a positive pressure from fire growth through firefighter suppression. Bedrooms 2, 3, and 4 were closed off from the fire area, which resulted in little to no pressure change within those bedrooms.



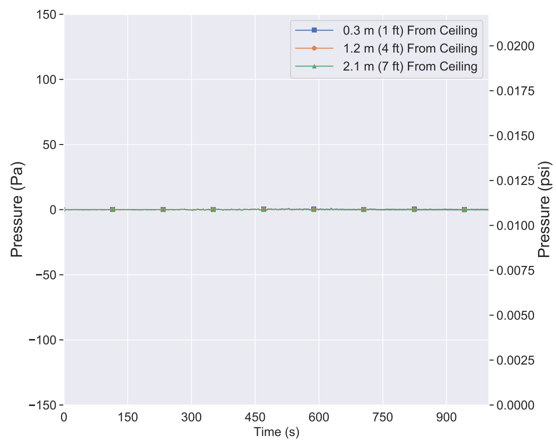
(a) Bedroom 1 Pressure



(b) Bedroom 2 Pressure



(c) Bedroom 3 Pressure



(d) Bedroom 4 Pressure

Figure 5.44: Experiment 8, front door and family room window open, pressures in second floor rooms.

5.2 Kitchen Fire

The kitchen fire experiment in the two story structure had a similar fuel package to the kitchen experiments in the single story, but the structure geometry was different. The ignition was located approximately 0.9 m (3 ft) above the floor, and the fuel package consisted of many solid fuels, including medium density fiberboard cabinets, plastics and plastic laminates, and vinyl flooring. The ignition package included an electrically modified (i.e., all thermal fuse protection was removed) coffee maker. The 12-cup, plastic shrouded coffee maker had 50 0.23 L (8 fl. oz) capacity expanded polystyrene hot serve cups arranged in three stacks on the right of the coffee maker, and a 0.45 kg (16 oz) bag of potato chips on the left side.

The fuels in the cabinet above the ignition package included: 1 kg (2.2 lb) of 0.53 L (18 oz) capacity polyethylene terephthalate (PET) drinking cups, and a 0.45 kg (16 oz) bag of potato chips.

The experiment was conducted with the front door open and all of the other exterior vents closed. On the interior, the door to bedroom 1 was open and all of the other interior doors were closed.

To start the fire, the coffee maker was plugged in an energized circuit. As the thermal element continued to heat without any thermostatic control or protection, the plastic in the area of the heating element began to pyrolyze, and then the gaseous vapors ignited. The time from the coffee maker being energized to flaming ignition was 4 min and 15 s. Once the flaming occurred, this time was considered time zero or the start of the fire experiment.

5.2.1 Front Door Open

Experiment 5

The fire began with flaming ignition of the coffee maker, which was positioned on the kitchen counter to the right of the range. Within one minute after ignition, intermittent flames contacted the underside of the wall cabinet. Three minutes after ignition, the flames were steadily impinging on the underside of the wall cabinet. The fire continued to grow with the flames spreading across the underside of the wall cabinet. Flames extended up both sides and the front face of the overhanging wall cabinet at 255 s after ignition. Smoke had been spreading across the kitchen ceiling. At this point in the fire, the smoke had reached the ceiling of the family room.

The fire continued to grow in the kitchen. At 285 s after ignition, the flames reached the kitchen ceiling. Thirty seconds later, the wall cabinet and adjacent cabinet above the range were fully involved in fire. Smoke began to flow out of the open front doorway at 325 s after ignition. At 7 min after ignition, flames spread across the top of the cabinets to the left of the area of origin and a hot gas layer approximately 1 m (3.3 ft) thick had developed under the ceiling across the entire first floor. Flames began spreading across the kitchen ceiling at 515 s after ignition. and black smoke flowed out of the upper half of the open front doorway.

The transition to flashover started approximately 9 min after ignition. Ten seconds later portions of the kitchen floor auto-ignited. The smoke flow out of the open front doorway increased at 565 s after ignition, and by 580 s after ignition, the front doorway appeared to be a unidirectional exhaust vent. Both the exhaust pressure and smoke flow increased. Post-flashover, the fire and smoke exhaust pressure appeared to have decreased. Firefighters opened the kitchen door at 980 s after ignition, and flames on the kitchen counter became visible again. At 1025 s firefighters started to extinguish hot spots in the kitchen. Table 5.7 provides a timeline of events.

Table 5.7: Timeline for Experiment 5, Kitchen Fire with Front Door Open

Time (s)	Event
0	Flaming ignition of coffeepot
60	Steady burning, flames intermittently contact underside of wall cabinet
180	Flames impinging on underside of wall cabinet
245	Flames have spread across underside of wall cabinet
255	Flame have extended up both sides and the front face of the wall cabinet, smoke spread to the ceiling of the family room
285	Fire continues to grow in kitchen, flames have reached the ceiling
315	Wall cabinet and adjacent cabinet above range fully involved in fire
325	Smoke begins to flow out of front doorway
420	Flames spreading across the top of cabinets to the left of the area of origin, hot gas layer within 1 m of the first floor
515	Flames spreading across kitchen ceiling, black smoke flowing out of the upper half of the front doorway
550	Transition to flashover, auto-ignition of kitchen floor
565	Smoke flow out of front doorway has increased
580	Front doorway appears to be a full exhaust vent, exhaust pressure and smoke flow has increased
645	Fire and pressure appears to have decreased
980	Firefighters open kitchen door, fire on kitchen counter is visible again
1025	Firefighters extinguishing hot spots in kitchen

Figure 5.45 shows the temperatures measured at the thermocouple array located in the kitchen. As the fire from the coffee maker spread to the cabinets, the temperature near the ceiling began to increase rapidly. Because the kitchen ceiling is open to the family room and the dining room, the development of a hot gas layer in the kitchen was delayed. Seven minutes after ignition, the smoke appeared to be within 0.3 m (1 ft) of the upper level floor, within a 1 m (3.3 m) of the lower level floor in the rooms other than the kitchen. Even though flames were spreading across the kitchen ceiling, no hot gas layer had developed within the kitchen yet. At 550 s after ignition, the radiation from the flames caused the kitchen flooring to auto-ignite. This led to the rapid increase in temperatures in the kitchen. The fire in the kitchen flashed over and burned until the excess fuel had been consumed. Once the fire became fuel limited, the temperatures began to decrease and reached a stratified steady state prior to suppression at 1025 s after ignition.

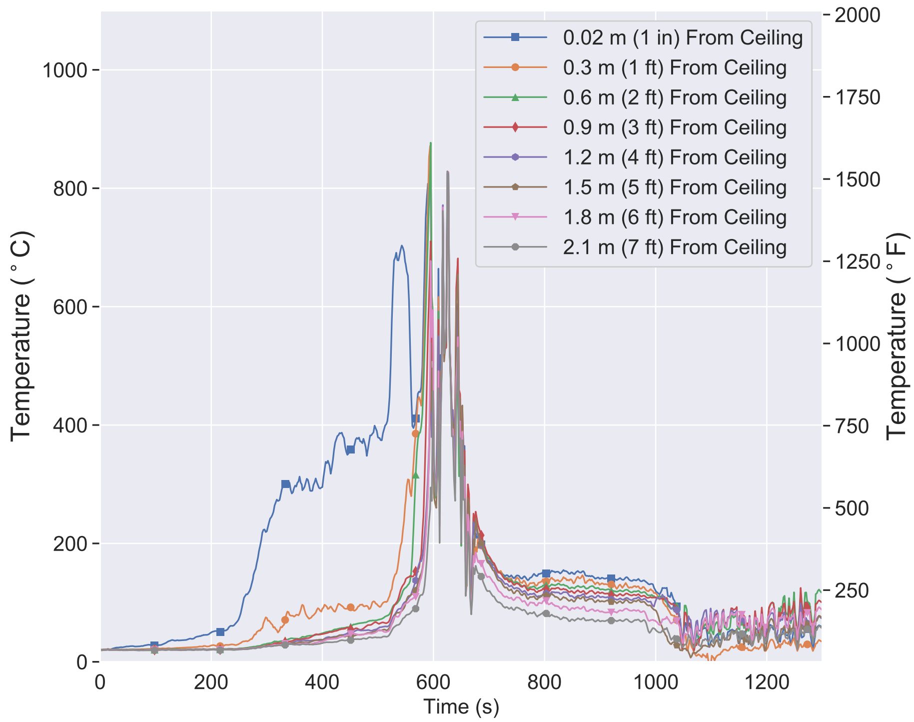


Figure 5.45: Experiment 5, front door open, kitchen temperatures versus time.

The temperatures measured in the open front doorway (see Figure 5.46) were also slow to increase. Basically, the upper volume of the family room, hall, and foyer needed to be filled with smoke prior to the neutral plane dropping below the level of the lintel of the doorway. The first temperature increase occurred more than 5 min after ignition. Once the kitchen flashed over, the temperatures increased at all elevations of the doorway. Post-flashover the temperatures at the doorway decreased until suppression.

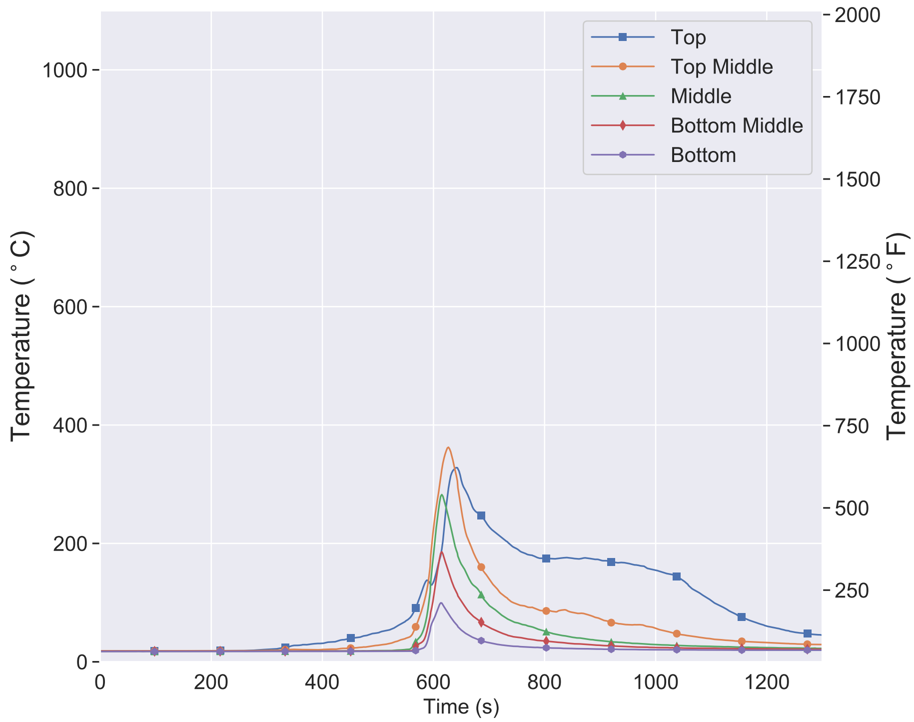
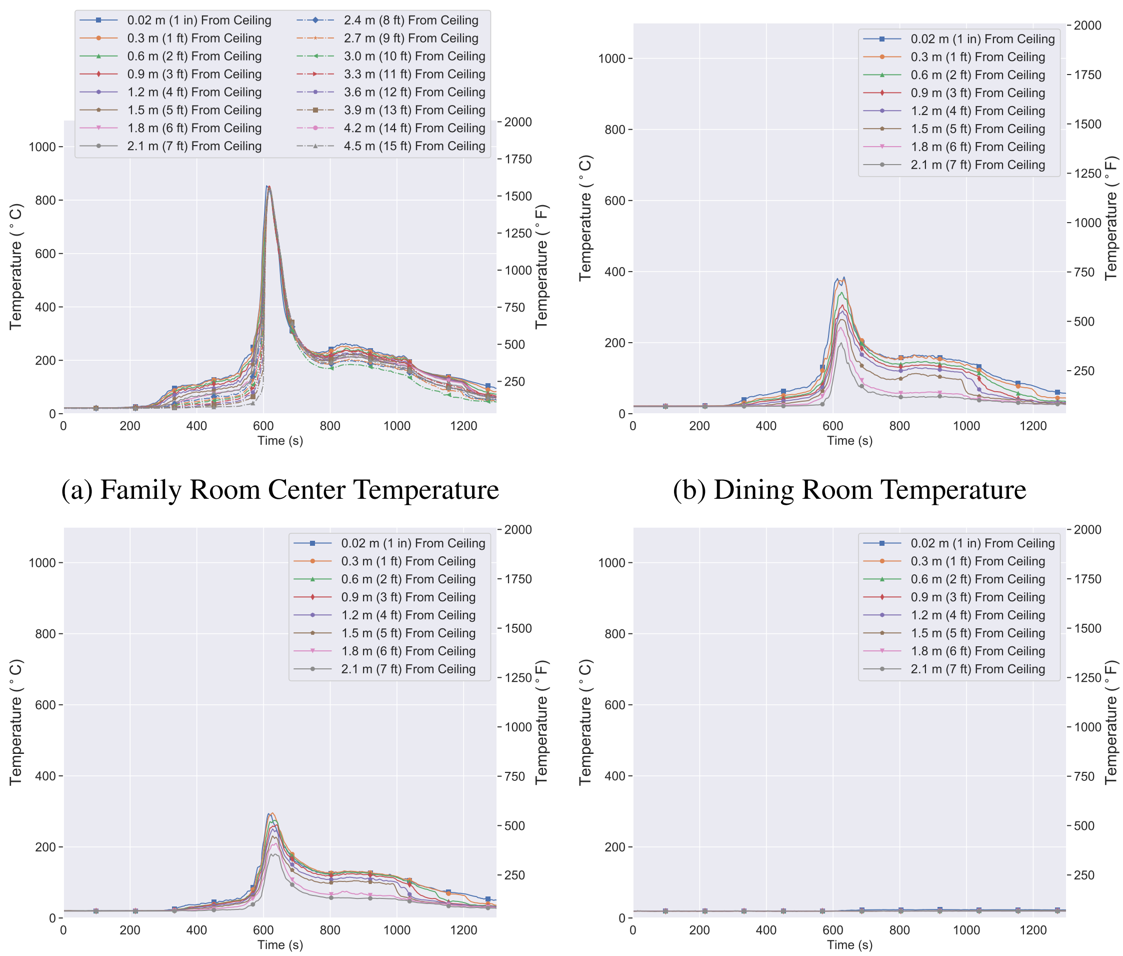


Figure 5.46: Experiment 5, front door open, front door temperatures versus time.

The temperature history for the four other rooms on the lower level of the structure appear in Figure 5.47. The family room was the collection area for much of the heat that was generated during the fire. Figure 5.47a shows that when the kitchen flashed over at approximately 600 s, the temperature conditions in the family room followed. This may lead some to think the family room also flashed over. That was not the case. The family room was carpeted and had a sofa installed. Post-test, neither the carpeting nor the sofa had any signs of thermal damage. So while the family room was filled with hot gases for a short time, it is likely that the gases were not burning.

The dining room and living room temperatures followed the same trends as the temperature in the kitchen. The dining room, which was next to the kitchen, had peak temperatures of almost 400 °C (752 °F) and the living room which was located further away from the kitchen had peak temperatures of almost 300 °C (572 °F). The den, also shown in Figure 5.47, was closed and therefore did not experience a temperature change.



(a) Family Room Center Temperature

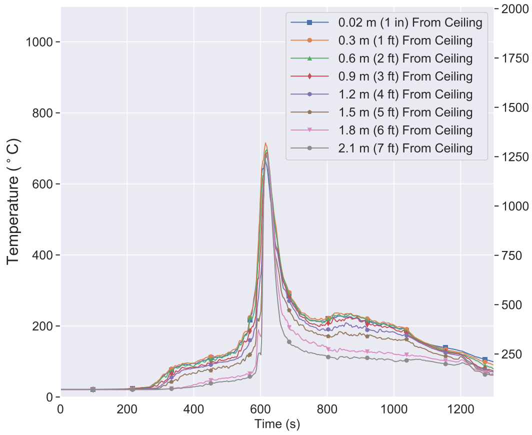
(b) Dining Room Temperature

(c) Living Room Temperature

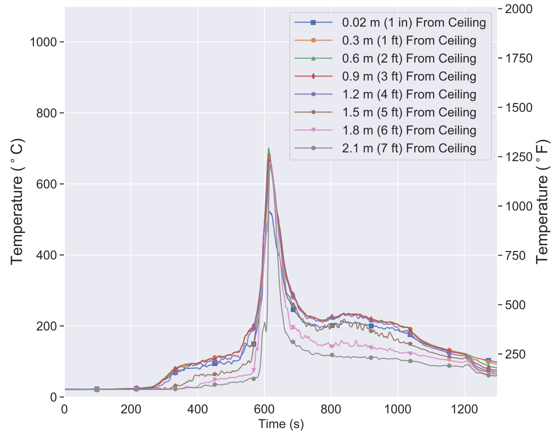
(d) Den Temperature

Figure 5.47: Experiment 5, front door open, temperature time histories for family room and other first floor rooms

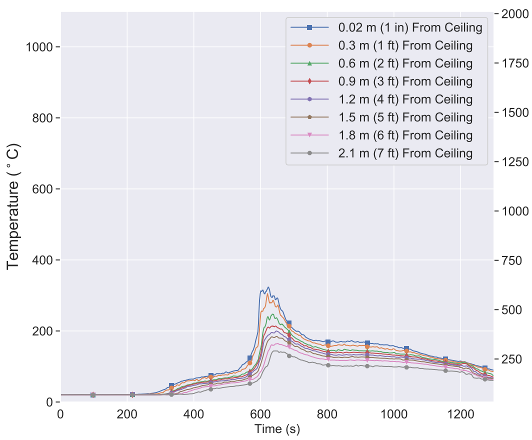
Figure 5.48 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedroom 1 were open to the fire area. The mid-hall and end-hall array temperatures shown in Figures 5.40a and 5.48b had the most similar temperatures and treads as the temperatures in the family room. These arrays were in the exhaust flow of the hot gases as they flowed from the family room into the foyer and down toward the open front door. Bedroom 1 was not in the main upper level flow path, and therefore had lower temperatures than the hallway arrays. Bedrooms 2, 3, and 4 were isolated from the fire area by having the doorways closed off, hence there was little to no increase in temperature in the bedrooms.



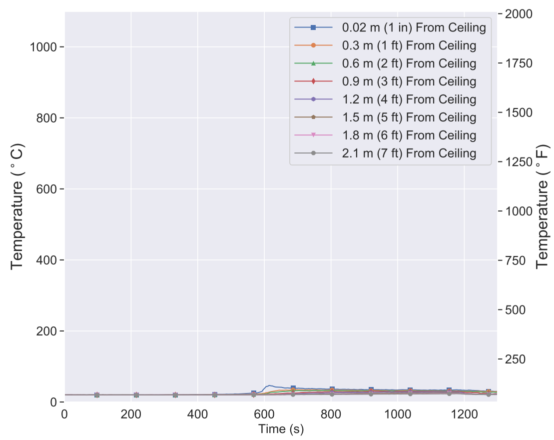
(a) Mid-Hall Temperature



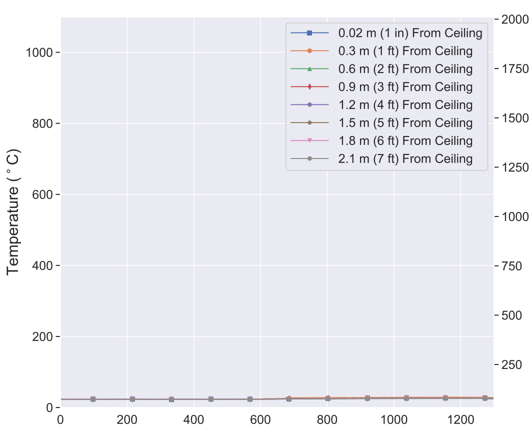
(b) End-Hall Temperature



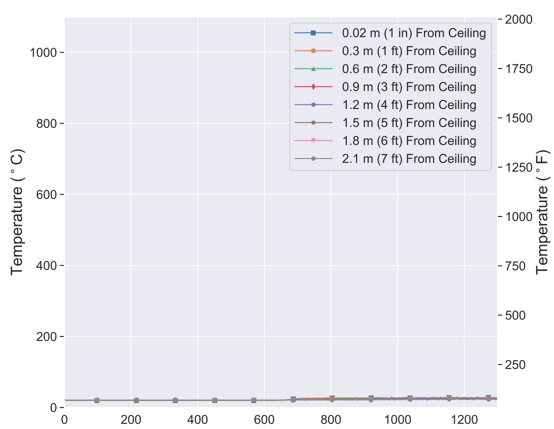
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature



(f) Bedroom 4 Temperature

Figure 5.48: Experiment 5, front door open, temperature time histories for second floor hallway and bedrooms.

The velocities measured in the open front doorway appear in Figure 5.49. From approximately 5 min after ignition the doorway was served as a bidirectional vent through the transition to flashover. As the flames were spreading across the ceiling in the kitchen leading up to flashover, the doorway became a unidirectional exhaust vent. As the temperatures decreased and stabilized, the doorway returned to bidirectional vent status through the end of the experiment.

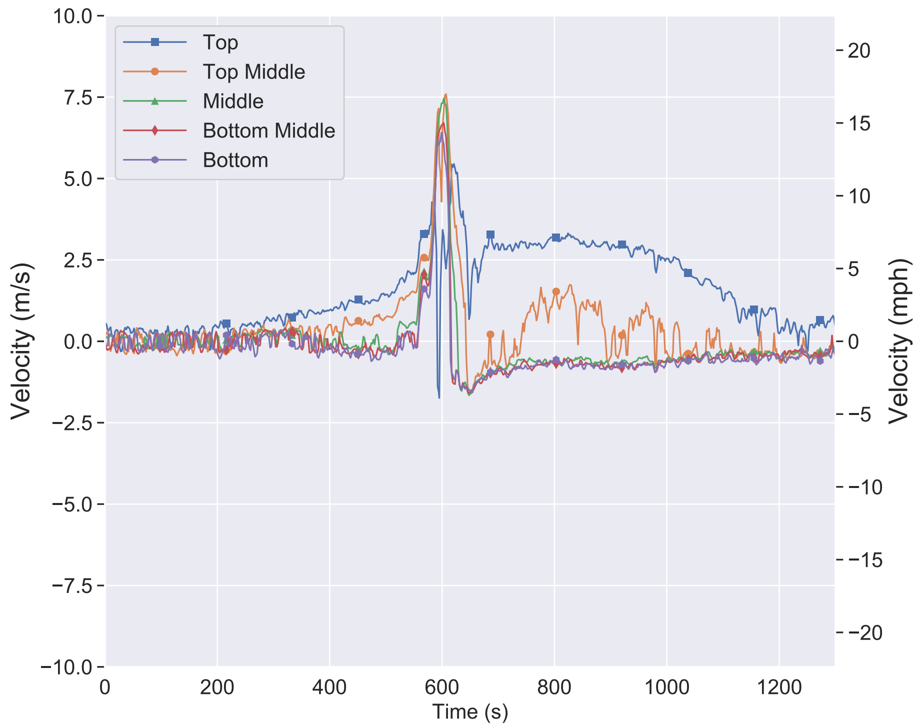
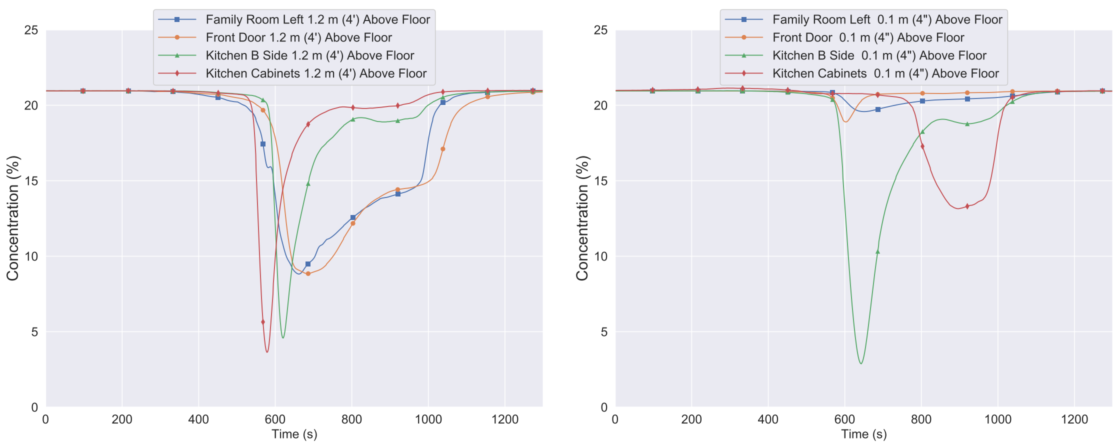


Figure 5.49: Experiment 5, front door open, front door velocity versus time.

The oxygen concentrations are presented in Figure 5.50 at two different elevations: Figure 5.50a (left) shows the oxygen concentrations at different positions 1.2 m (4 ft) above the floor, and Figure 5.50b (right) shows the oxygen concentrations at different positions 0.1 m (4 in.) above the floor. Significant differences in oxygen concentration appear based on the measurement location.

At the 1.2 m (4 ft) elevation, oxygen concentrations at the four locations dropped as the smoke layer built up within the structure. The family room location and front door locations showed an early initial decrease in oxygen as smoke filled the open two story void before building in the kitchen. However, as the kitchen transitioned to flashover, the two 1.2 m (4 ft) probes (side B and at the cabinets), both had more severe decreases, dropping below 5%. This coincides with the peak temperatures in the kitchen. The low oxygen concentrations forced the fire into a decay phase. As the heat release from the fire dropped, temperatures dropped, and oxygen concentrations began to recover. The front door and family room locations dropped below 10% slightly after the kitchen flashed over, below levels that typically would support combustion. The oxygen concentrations at both locations increased, but more slowly as combustion gasses remained in the family room because of the open second story level and gases continued to flow out of the front door.

For both the front door and family room at the 0.1 m (4 in.) level, both sensors showed slight decreases in oxygen concentration when the kitchen transitioned to flashover, dropping to 19% and 19.5%, respectively. There was an initial push corresponding to when the front door was in full exhaust that led to the drop at both locations, but soon after, the oxygen levels began to increase. The kitchen sensors showed two different responses. The 0.1 m (4 in.) side b sensor dropped similarly to the 1.2 m (4 ft) elevation. As the kitchen transitioned to flashover, the oxygen dropped below 5% before recovering as fire was in decay. The lower oxygen sensor in the cabinet location only dropped to 13%, was slower to respond, and has a flatter response profile. At the 0.1 m, this sensor was located in the gap between cabinets where a dishwasher might typically be installed. The void and the counter top restricted flow to the sensor which caused the muted response.

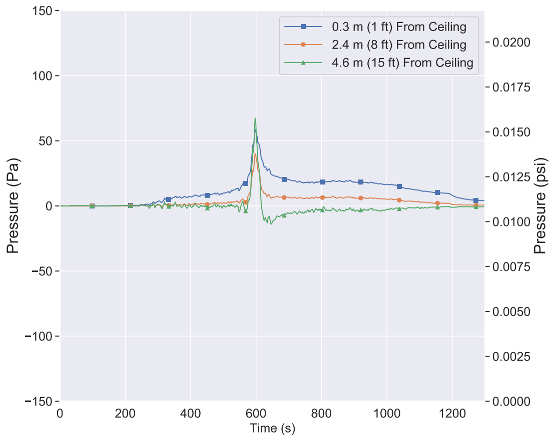


(a) Oxygen 1.2 m Above Floor

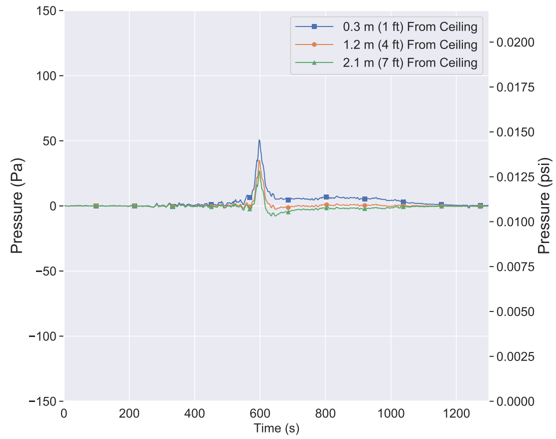
(b) Oxygen 0.1 m Above Floor

Figure 5.50: Experiment 5, front door open, oxygen concentrations versus time.

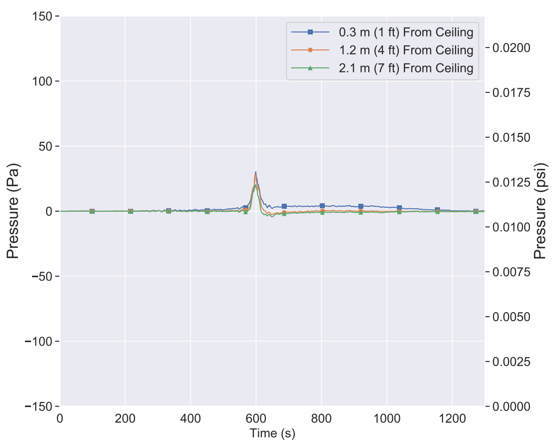
Figure 5.51 shows the pressures from the rooms on the lower level. The peak pressure in the kitchen, the room of fire origin, was approximately 50 Pa. In the previous experiments, the peak pressure occurred in the room of fire origin. In this experiment, the peak pressures, approximately 70 Pa, occurred in the family room. The upper level of the family room was serving as an energy reservoir, It appears that the burst of energy released in the kitchen during flashover flowing into the family room where the expanding gases had a higher level of confinement than they had in the kitchen, hence the higher pressure in a room adjacent to the fire room. Post-flashover, the slightly negative pressures near the floor in the four open rooms allowed for the higher pressure outside air to flow into the structure. In this experiment, the den was closed off from the fire area so the pressure in the den did not change.



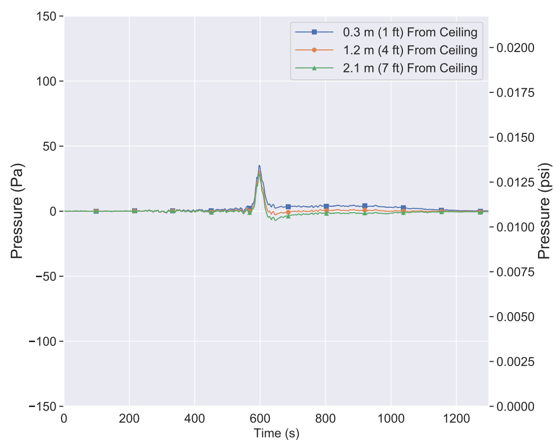
(a) Family Room Pressure



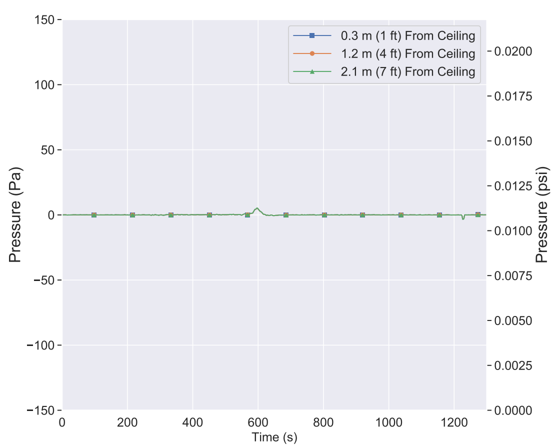
(b) Kitchen Pressure



(c) Front Door Pressure



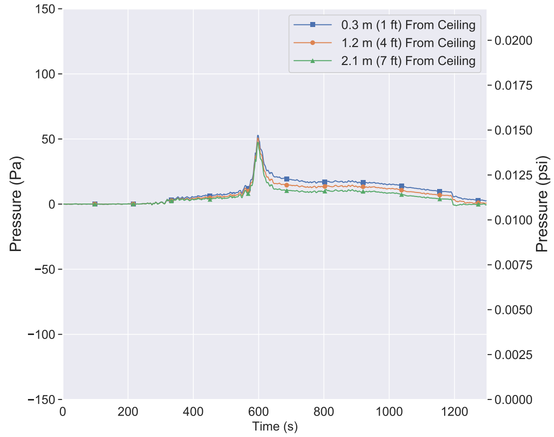
(d) Living Room Pressure



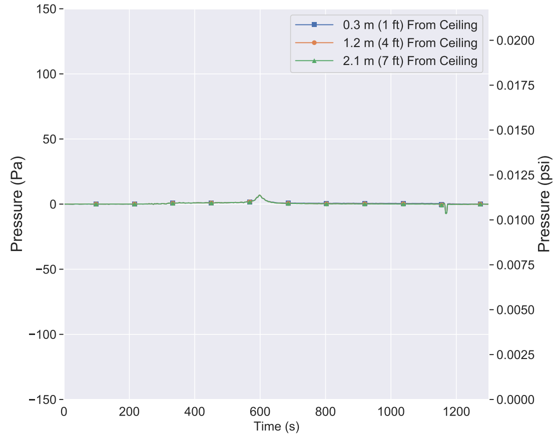
(e) Den Pressure

Figure 5.51: Experiment 5, front door open, pressures in first floor rooms.

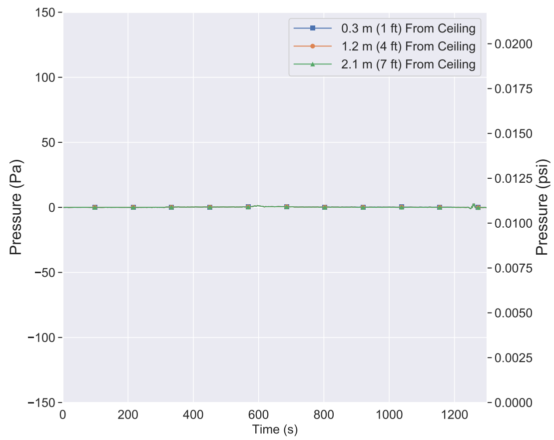
The pressures on the upper level are given in Figure 5.52. Bedroom 1 was the only room open to the fire area. Bedroom 1 maintained a positive pressure from fire growth through firefighter suppression. Bedroom 1 is positioned above the neutral plane in the structure. Bedrooms 2, 3, and 4 were closed off from the fire area which resulted in little to no pressure change within those bed rooms.



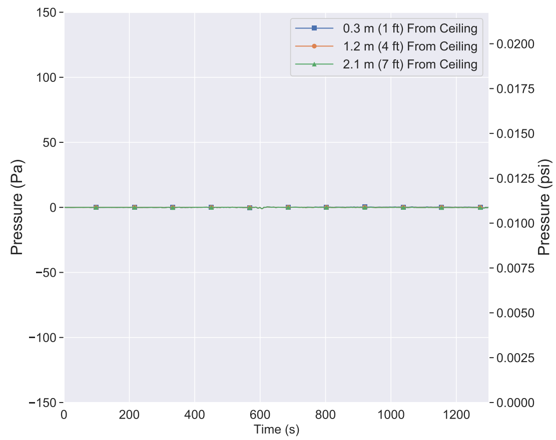
(a) Bedroom 1 Pressure



(b) Bedroom 2 Pressure



(c) Bedroom 3 Pressure



(d) Bedroom 4 Pressure

Figure 5.52: Experiment 5, front door open, pressures in second floor rooms.

5.3 Laundry Room

Most of the experiments conducted in the two story structure used a large room that was part of the open plan area of the structure. The laundry room experiment was different because the laundry room was a smaller room that was connected to the kitchen via a doorway and a hall. The only ventilation available to the laundry room was through a 0.75 m (2.46 ft) wide door.

Similar to the kitchen experiments, the laundry room fire was ignited at an elevated position, on top of the washing machine. This ignition location and the size of the room had the potential for the fire to become ventilation limited sooner in its development.

5.3.1 Front Door Open

Experiment 6

The fire began with the ignition of a bedspread and two pillows in a plastic laundry basket on top of the washing machine. The fire was ignited with a remote operated electric match. Within 60 s after ignition, the fire grew inside the laundry basket and light smoke flowed across the laundry room ceiling and into the hallway. At 90 s light grey smoke began to flow into the kitchen. Even though the fire was still contained to the laundry basket, at 150 s after ignition a 0.6 m (2 ft) thick hot gas layer had built up within the laundry room. In addition, smoke had flowed down the hallway and spread across the width of the kitchen ceiling.

Three minutes after ignition, the smoke spread and flowed across the ceiling of the family room. One minute later, the fire was still burning on top of the washer, and the hot gas layer in the laundry room had increased to 0.9 m (3 ft) thick. The hot gas layer in the kitchen was 0.6 m (2 ft) thick, and the hot gas layer under the second floor ceiling had built to 1.2 m (3.9 ft) thick.

The cardboard boxes next to the washing machine ignited at 245 s into the experiment, and flames had spread across the ceiling of the laundry room by 285 s after ignition. Within 5 min of ignition, smoke flowed out the open front doorway. At 475 s after ignition, the wall cabinet over the dryer started burning, and then flames exited the laundry room and flowed into the hallway. The laundry room door ignited at 525 s.

The hot gas layer began burning at 555 s, which led to flashover. Seconds later, fuels in the laundry room began to auto-ignite. The flooring in the hallway began burning at 615 s after ignition. At 770 s, the fire in the laundry room decreased, which resulted in the cessation of flames entering the hallway. However, the flames already in the hallway continued to spread across its full length (780 s after ignition). The fire in the hallway decreased 20 s later, and smoke continued to flow out of the upper third of the open front door.

Based on thermal imaging video, the heat flow entering the kitchen was observed to be oscillating up and down. Fifteen minutes after ignition, the flow increased. At sixteen minutes after ignition, hot gas flow into the kitchen decreased. The hot gas flow into the kitchen then increased at 1030 s and then decreased again at 1140 s. Twenty minutes after ignition, firefighters closed the front door, flames burned out of the gaps around the laundry room shutter. Exterior flames on that window shutter were extinguished at 1240 s. About a minute later, the firefighters opened the window shutters and suppressed the fire. Table 5.8 provides a timeline of events.

Table 5.8: Timeline for Experiment 6, Laundry Room Fire with Front Door Open

Time (s)	Event
0	Flaming ignition of laundry basket on washer
60	Fire growing within laundry basket, light smoke flowing across laundry room ceiling and into hallway
90	Light smoke flowing into kitchen
150	Fire still within laundry basket, HGL in laundry room 0.6 m thick, smoke has spread across the width of the kitchen ceiling
180	Smoke flowing across the ceiling of the family room
240	Fire still burning on top of the washer, HGL in the laundry room 0.9 m thick, HGL in kitchen is 0.6 m thick, HGL under second floor ceiling, 1.2 m thick
245	Cardboard boxes next to washing machine have ignited
285	Flames spreading across ceiling of laundry room
300	Smoke has started to flow out of front doorway
475	Flames exiting laundry room into hallway, wall cabinet over dryer is burning
525	Door has ignited
555	Hot gas layer in laundry room is burning, transition to flashover
575	Laundry room floor begins to auto-ignite
615	Flooring in hallway is burning
770	Fire in laundry room has decreased, flames no longer exiting into hall
780	Flames have spread down the length of the hallway
800	Fire in hallway has decreased, smoke continues to flow out of the upper third of the front door
900	Based on thermal imager video, the heat flow entering the kitchen is oscillating up and down, and the flow has increased
960	Hot gas flow into kitchen has decreased
1030	Hot gas flow into kitchen has increased
1140	Hot gas flow into kitchen has decreased
1200	Firefighters close front door, flames began burning out of the gaps around the laundry room window shutter
1240	Exterior flames on window shutter extinguished
1295	Firefighters open laundry room shutter and suppress fire with a hose stream through the window opening

Figure 5.53 provides the time history of the temperatures in the laundry room. The temperature increase for the first 250 s was generated by the burning bedding in the laundry basket. The second temperature increase was the result of the cardboard commodity boxes burning. The third increase

in temperatures, which led to flashover was caused by the wall cabinet and wood door burning. Post-flashover the temperatures decreased and then increased. This started a cycle of increases and decreases that continued for about 8 minutes until the front door was closed. Closing the front door stopped the oxygen supply to the laundry room and temperatures continued to decrease until suppression.

The temperature cycles ranged from a low of 520 °C (968 °F) to peaks of 1200 °C (2192 °F). The time period and the amplitude of the temperature range appeared to increase with each cycle. As the rest of the data is reviewed below, the cyclic behavior will be seen in temperatures in other rooms, velocity measures at the front door and oxygen concentrations in the kitchen, close to the hallway to the laundry room. This oscillations are similar to those discussed by Carman with regard to elevated fires [36]. While this fire was started in an elevated position, at the time of the oscillations most of the fuels had collapsed and were burning near floor level. Beyler also noted oscillatory burning behavior in ventilation controlled layer burning [37].

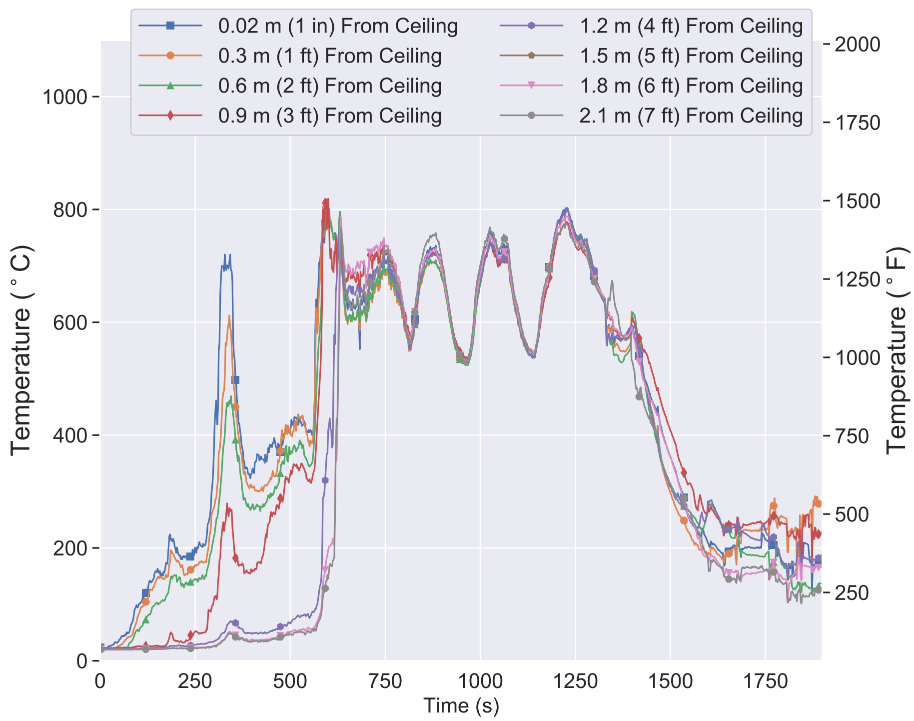


Figure 5.53: Experiment 6, front door open, laundry room temperatures versus time.

The front door was the only exterior vent for this experiment. The temperatures measured in the front door opening appears in Figure 5.54. The main temperature increases are limited to the top third of the doorway. The elevated temperatures in the door have small oscillations that began post-flashover and end with the closure of the front door.

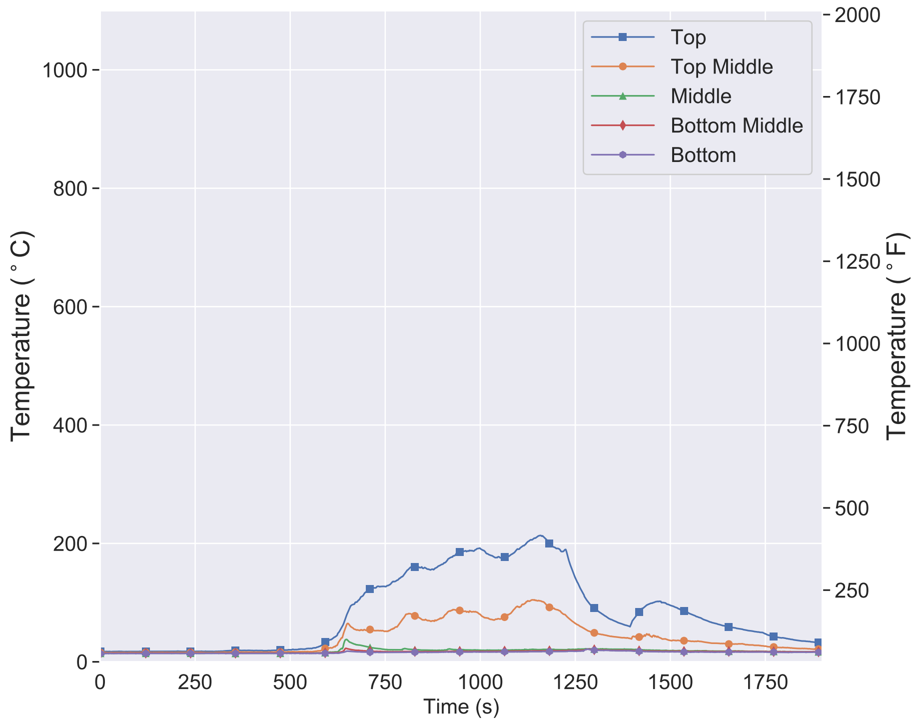
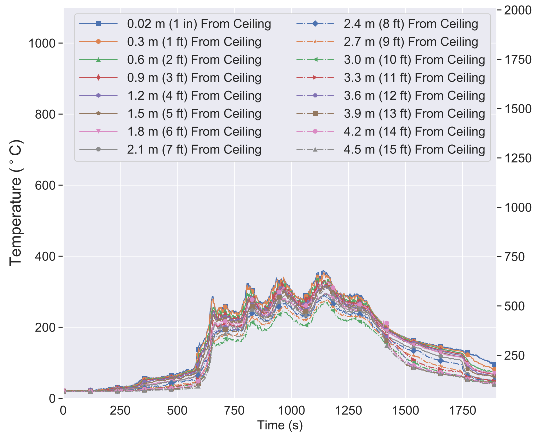


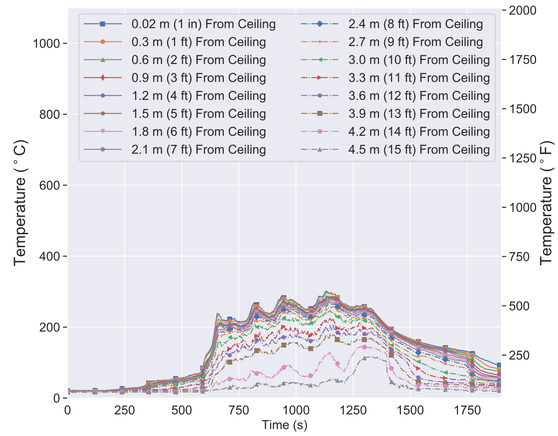
Figure 5.54: Experiment 6, front door open, front door temperatures versus time.

Figure 5.55 contains six graphs with the temperatures from the thermocouple arrays that were located in the areas on the lower level. The five rooms open to fire room were the famlily order from the closest to the laundry room to the furthest, were: kitchen, family room, dining room, foyer, and living room. The rooms in the flow path between the laundry room and the front door were the kitchen, the family room, and the foyer. These three rooms had the highest peak temperatures outside of the laundry room.

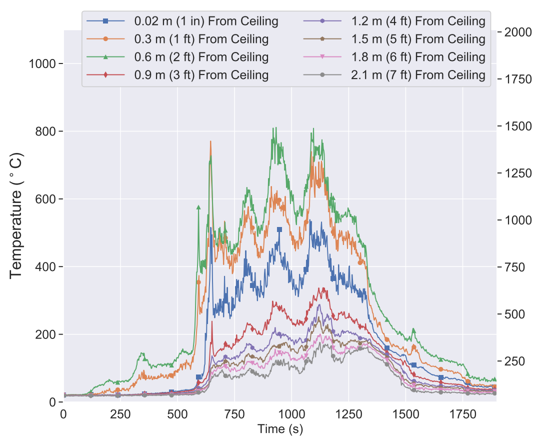
Along the flow path, the closer room (kitchen) had the higher temperatures, while the furthest room (foyer) had the lower temperatures. The dining room and living room were outside of the flow path and had the lowest temperatures on the lower level. All of the temperature time histories display the cyclic temperature behavior. The den had no temperature increase as a result of being closed off from the fire area.



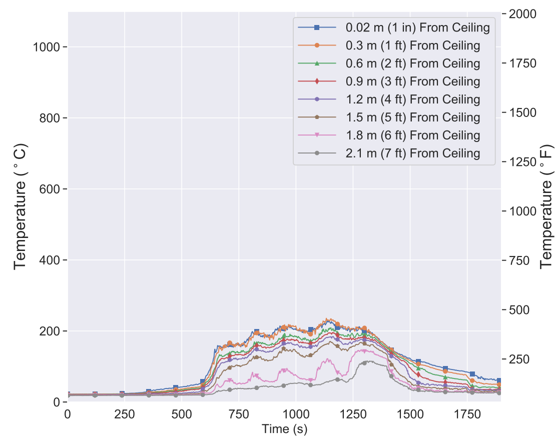
(a) Family Room Center Temperature



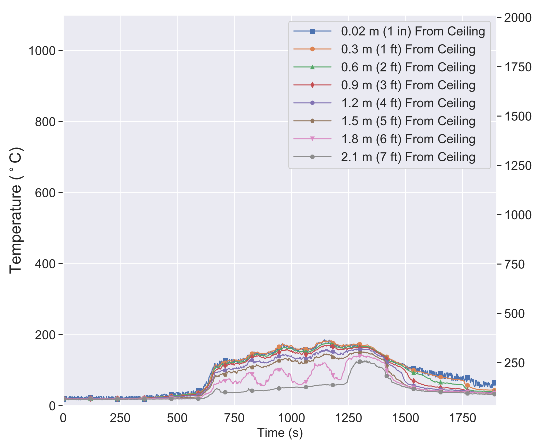
(b) Foyer Temperature



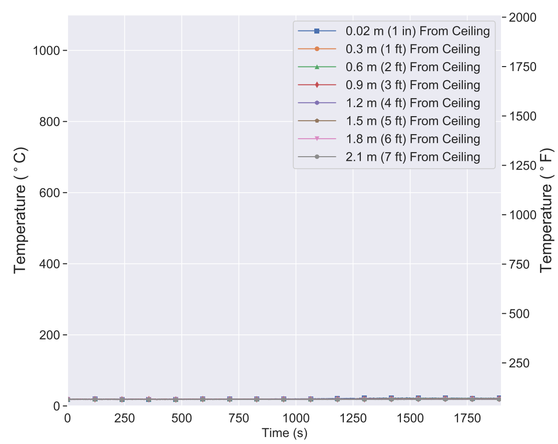
(c) Kitchen Temperature



(d) Dining Room Temperature



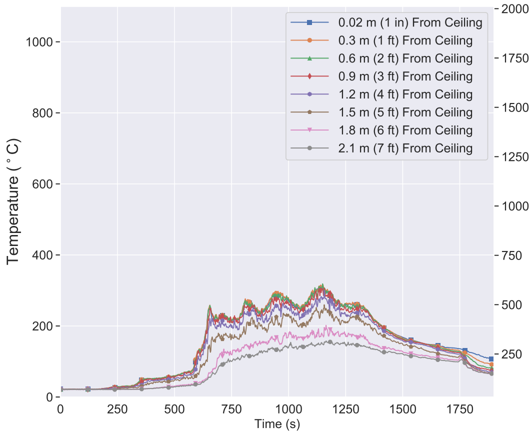
(e) Living Room Temperature



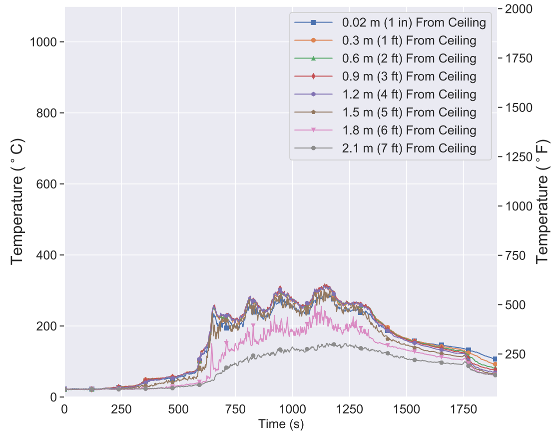
(f) Den Temperature

Figure 5.55: Experiment 6, front door open, temperature time histories for family room and other first floor rooms.

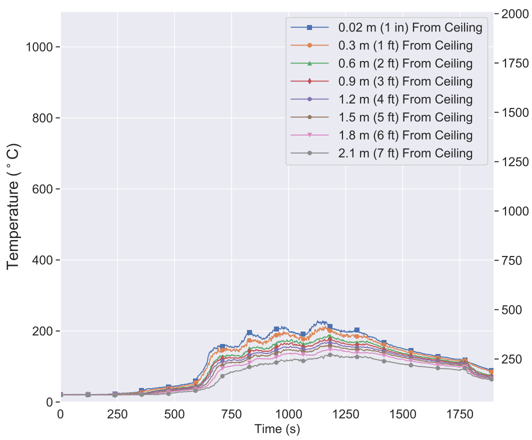
Figure 5.56 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedroom 1 were open to the fire area. The mid-hall and end-hall array temperatures shown in Figures 5.56a and 5.56b had the most similar temperatures and trends as the temperatures in the family room. These arrays were in exhaust flow of the hot gases as they flowed from the family room into the foyer and down toward the open front door. Bedroom 1 was not in the main upper level flow path and therefore had lower temperatures than the hallway arrays. Bedrooms 2, 3, and 4 were isolated from the fire area by having the doorways closed off, hence there was little to no increase in temperature in the bedrooms.



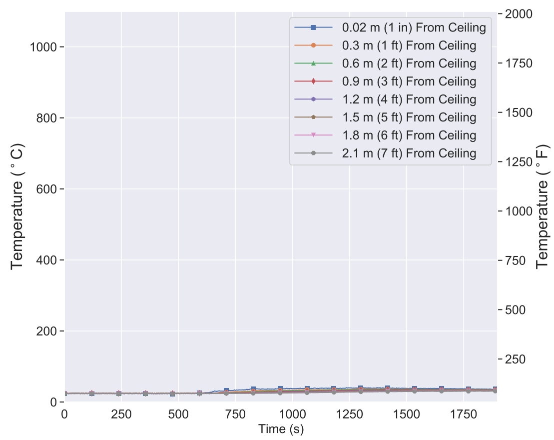
(a) Mid-Hall Temperature



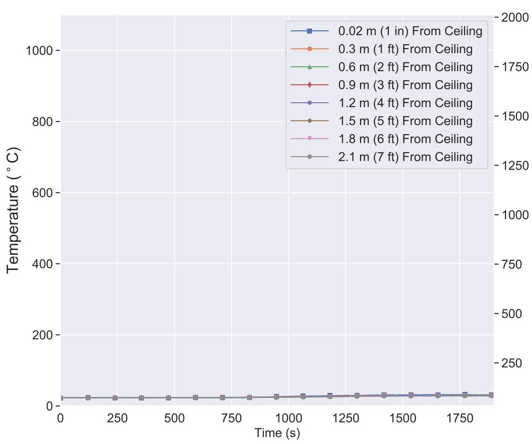
(b) End-Hall Temperature



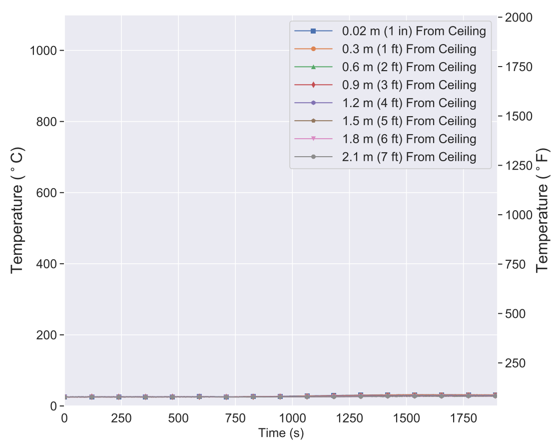
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature



(f) Bedroom 4 Temperature

Figure 5.56: Experiment 6, front door open, temperature time histories for second floor hallway and bedrooms.

The velocities measured in the front doorway appear in Figure 5.57. The exhaust flows through the door increased as the fire in the laundry room was transitioning to flashover. During the initial increased period, the doorway became a unidirectional exhaust vent. As the energy from the fire decreased post-flashover, the flows in the doorway stratified and the doorway returned to acting as a bidirectional vent. The temperature cycle trends can be seen in the velocity time histories.

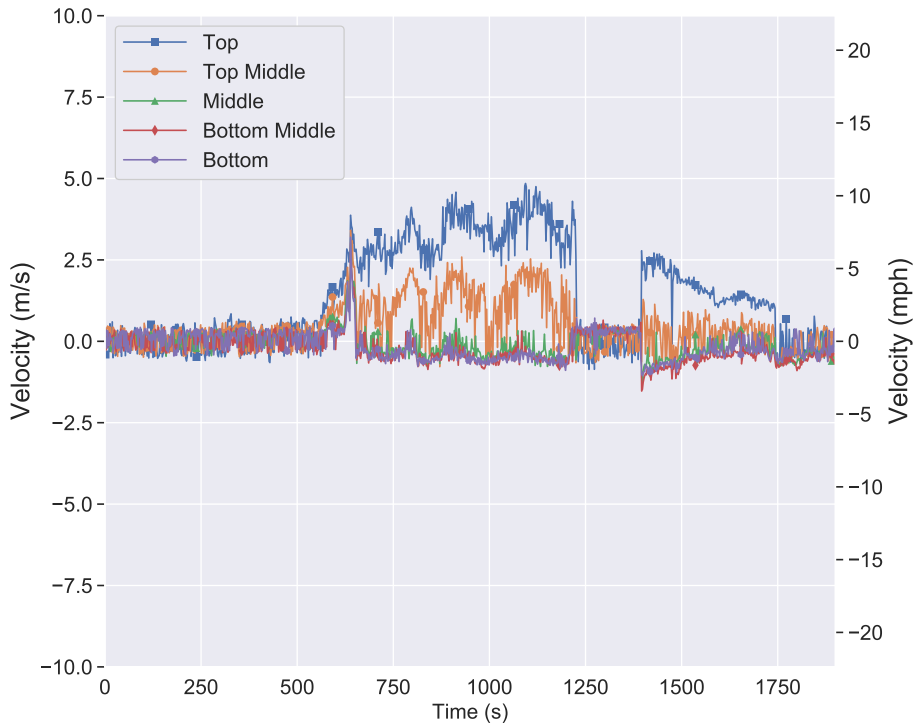


Figure 5.57: Experiment 6, front door open, front door velocity versus time.

The oxygen concentrations are presented in Figure 5.58. Significant differences in oxygen concentration are shown based on the measurement location. The graph on the left in Figure 5.58a shows the oxygen concentrations at different positions 0.1 m (4 in.) above the floor. The graph on the right in Figure 5.58b shows the oxygen concentrations at different positions 1.2 m (4 ft) above the floor.

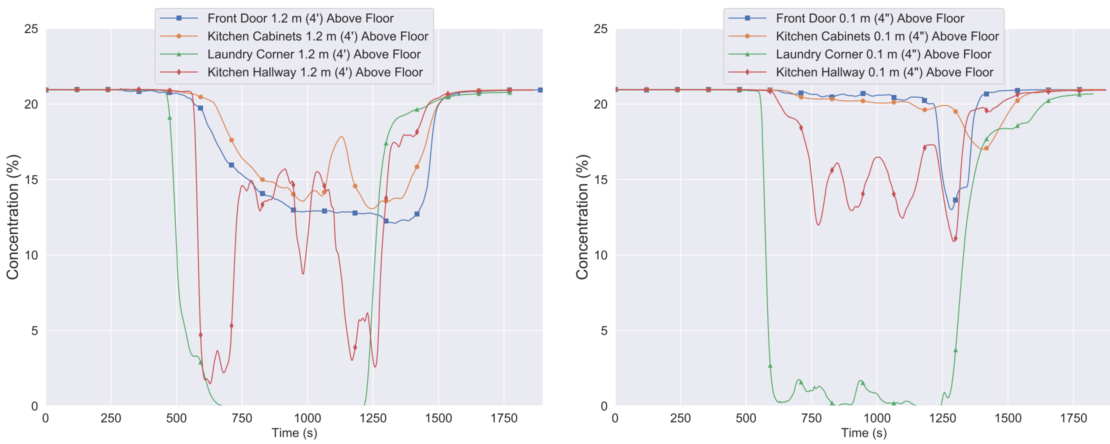
The oxygen concentrations measured at the doorway to the laundry room began to decrease as the wall cabinet was burning and the flames began to exit the laundry room. As the fire in the laundry room flashed over, both of the oxygen concentration values in the laundry room decreased to approximately 0% and remained there until the front door was closed.

The kitchen hallway oxygen sampling positions, located at the kitchen end of the hallway, had the greatest movement and cyclic oscillations. As the burning rate in the laundry room changed, the amount of oxygen at the kitchen hallway sampling positions also changed. As the flashover occurred in the laundry room, the oxygen concentrations at the 1.2 m (4 ft) above the floor position decreased from ambient to below 5% within 60 s. The oxygen concentration here stayed below 5% for almost 2 min. During this two minute period, the oxygen concentration at 0.1 m (4 in.) above the floor started to decrease, reaching a minimum concentration of 12%. Then the cyclic behavior started. From 720 s after ignition through 1120 s, the values at the 1.2 m (4 ft) and 0.1 m (4 in.) above the floor positions both cycled through an oxygen concentration range of the 9% to 17%. The energy flowing out of the laundry room and down the hallway reduced as the second decrease below 5% occurred at the 1.2 m (4 ft) level. Then the oxygen levels at both of these locations started to increase until the front door was closed, which caused another decrease in oxygen concentration. Once the laundry room was vented at 1295 s after ignition, the oxygen concentration at 0.1 m (4 in.) above the floor began to increase again. After the fire was extinguished and the structure was ventilated, the oxygen concentrations at all positions returned to 20.9%.

The oxygen sampling locations labeled kitchen cabinets were located in the back wall of the structure at the end on the kitchen cabinets near the kitchen door (basically, the point in the kitchen most remote from the kitchen hallway sampling locations). The oxygen concentrations measured at the kitchen cabinet location did not exhibit the cyclic changes. The oxygen concentrations measured at 1.2 m (4 ft) above the floor decreased post-flashover to levels between 10% and 15% and remained there for most of the fire until the structure was ventilated. There was one exception: For 100 s, starting at 1075 s after ignition, oxygen concentration increased to almost 18% before dropping back below 15%. At the location 0.1 m (4 in.) above the floor, the oxygen concentrations stayed near 20% throughout the experiment until after the start of suppression at 1295 s after ignition, when the oxygen concentration decreased to 17%.

The last pair of oxygen sampling locations were located in the foyer near the front door. The oxygen concentrations from the upper position started to decrease post-flashover. The oxygen concentration decreased below 15% at 770 s after ignition and remained in the 10% to 15% range until the structure was ventilated post-suppression. The position close to the floor measured oxygen concentrations near 20% from ignition, until the front door was closed at 1200 s after ignition. After 1200 s, the oxygen concentration decreased below 15%. The oxygen concentration began to increase again with the onset of suppression and ventilation.

The open front door served as a bidirectional vent providing the only exhaust and air intake to the fire in the laundry room. Qualitatively tracking the oxygen concentrations over time, one can see from the data that less oxygen was available during the fire at locations closer to the fire, and more oxygen was available closer to the floor and closer to the air intake.



(a) Oxygen 1.2 m Above Floor

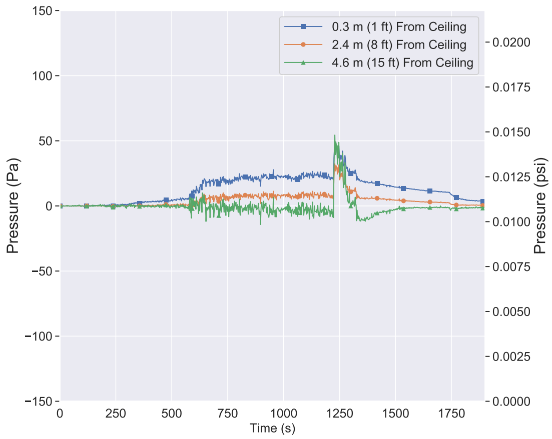
(b) Oxygen 0.1 m Above Floor

Figure 5.58: Experiment 6, front door open, oxygen concentrations versus time.

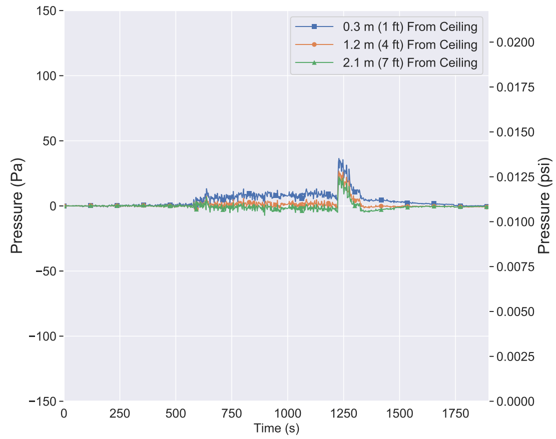
Figure 5.59 shows the pressures from the rooms on the lower level outside of the laundry room. The open front door acted as an exhaust (pressure relief) and intake vent. From the time of ignition, until the closure of the front door at 1200 s after ignition, the trends of the pressures in the open lower level rooms are the same. The pressure gradient in each room had positive pressures near the ceiling and negative pressures near the floor. As noted before, this pressure difference accounted for the circulation of hot gases out of the structure and air flow into the structure through the open front door.

The pressure location near the ceiling in the family room had measurements of approximately 25 Pa, which were the highest pressure measurements in the structure during post-flashover burning stage of the fire. The pressures in the upper level portion of the family room collected hot gases with no exhaust vent on the upper level, which in turn resulted in higher pressures on the lower level.

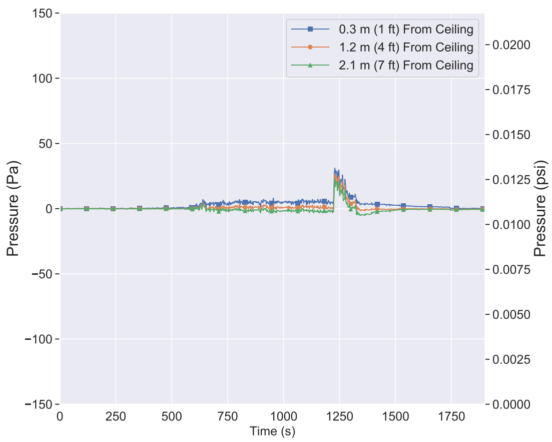
Closing the door at 1200 s after ignition generated a pressure increase, floor to ceiling, throughout the structure. The peak pressure in the family room was just over 50 Pa, while the peak pressure in the other rooms ranged from about 30 Pa to 35 Pa. When the door was closed, the increased pressure inside the structure forced hot gases through the gaps around the laundry room window shutter. The gases burned on the exterior of the structure and ignited the exterior of the shutters. In this experiment, the den was closed off from the fire area, so the pressure in the den did not change.



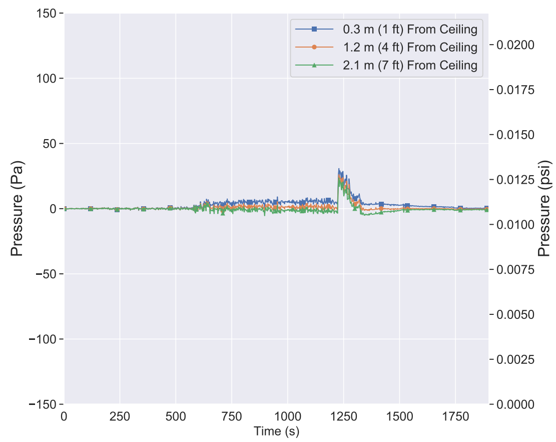
(a) Family Room Pressure



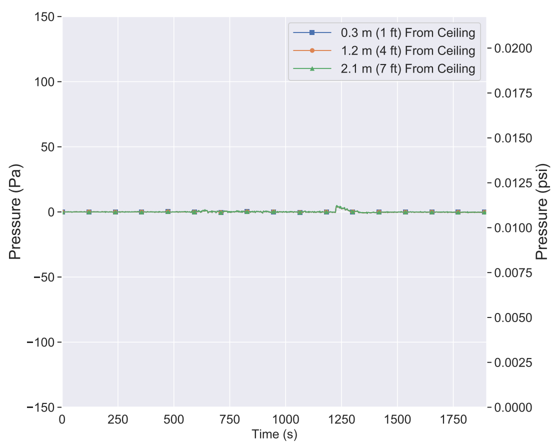
(b) Kitchen Pressure



(c) Front Door Pressure



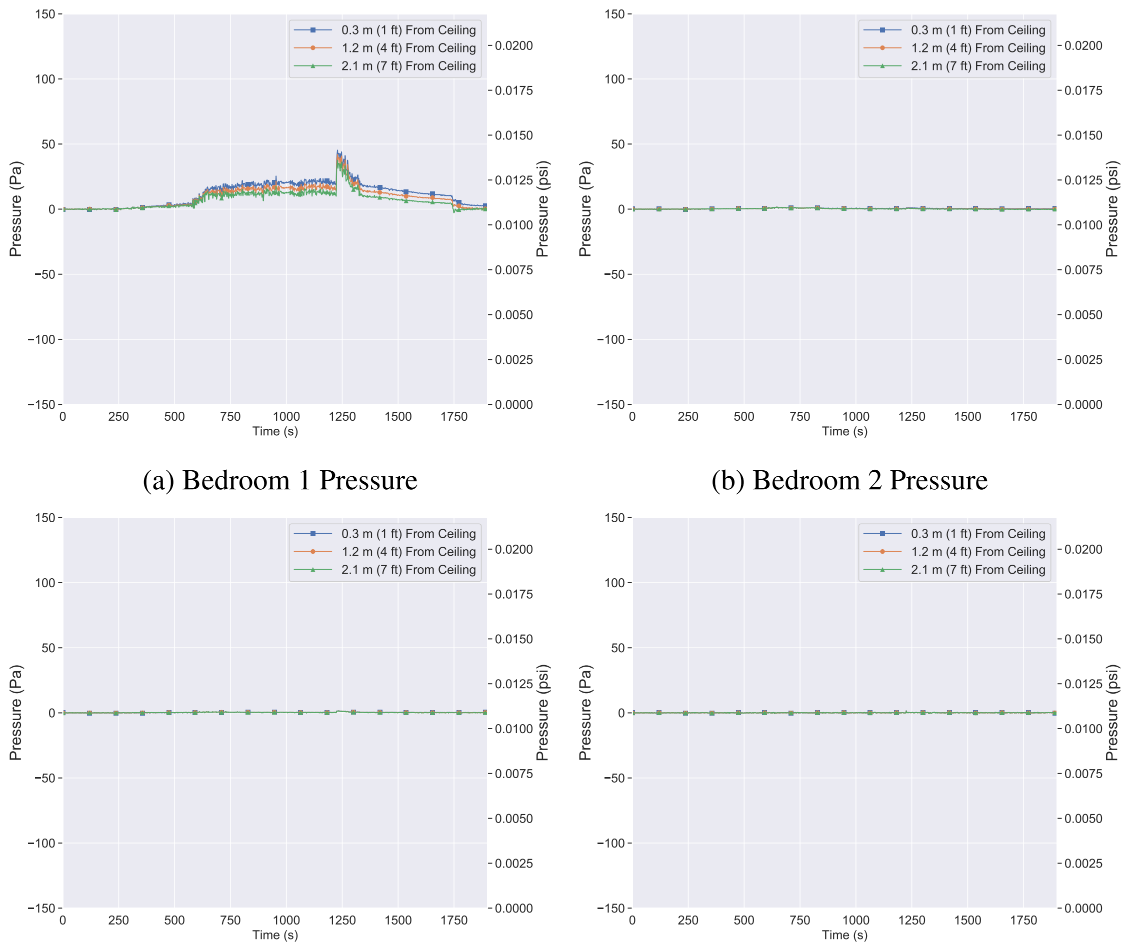
(d) Living Room Pressure



(e) Den Pressure

Figure 5.59: Experiment 6, front door open pressures in first floor rooms.

The pressures on the upper level appear in Figure 5.60. Bedroom 1 was the only room open to the fire area. The pressure trends in bedroom 1 were similar to the pressure in the upper portion of the family room. Bedroom 1 had a positive pressure from fire growth through suppression and ventilation, because there was no exhaust vent on the upper level and bedroom 1 was located above the neutral plane. The pressures in bedroom 1 spiked as a result of the front door closure in concert with the pressures throughout the structure. Bedrooms 2, 3, and 4 were closed off from the fire area which resulted in little to no pressure change within those bedrooms.



(a) Bedroom 1 Pressure

(b) Bedroom 2 Pressure

(c) Bedroom 3 Pressure

(d) Bedroom 4 Pressure

Figure 5.60: Experiment 6, front door open pressures in second floor rooms.

5.4 Den

Similar to the laundry room fire, in Experiment 6 the den was a relatively small room on the lower level of the two story structure. It was connected to the open plan area of the structure by a 0.72 m (2.4 ft) wide door way. The den also had a window opening that was 0.85 m (2.8 ft) wide, 1.46 m (4.8 ft) high and had a sill height 0.61 m (2.0 ft) above the floor. In terms of ventilation, this experiment was similar to Experiment 8, which had the area of origin in the family room, a window opening next to the ignition sofa, and the open front door as a remote vent. This experiment had a vent opening in the room of origin, and the open front door was the remote vent opening.

5.4.1 Front Door and Den Window Open

Experiment 7

The fire began with the ignition of the left side of the upholstered chair seat. Within 60 s after ignition, flames began to heat the gypsum board above and to the side of the chair back. Light gray smoke flowed out of the den doorway and window at 90 s. Smoke also began to flow into the kitchen. After 2 min, flames extended 1 m (3.3 ft) above the ignition seat cushion. A hot gas layer developed in the den approximately 0.6 m (2 ft) thick. At this point the smoke flow out of the open den doorway and the den window increased.

Within 150 s after ignition, smoke had spread across the family room (upper level) ceiling. At 3 min, flame was involved in less than half of the ignition chair, and the hot gas layer in the den was 0.9 m (3 ft) thick. At 220 s after ignition, flames exited the den doorway into the lower level of the house, and black smoke flowed out of the upper half of the den window. Smoke flow out of the open front doorway began 10 s later. The ottoman in front of the ignition chair began pyrolyzing at 4 min after ignition. Within seconds of that observation, the hot gas layer in the den began burning.

The ottoman and adjacent sofa had ignited by 255 s after ignition as the den transitioned through flashover. At 270 s the flames extended more than 2 m (6.6 ft) out of the upper half of the den doorway. Flames filled the open den window and extended up the back of the structure to the second floor. Black smoke exhausted out of the open front doorway from top to bottom. Five minutes after ignition, flames continued to flow out of the den doorway and open window, the smoke layer inside the house was within 0.5 m (1.6 ft) of the lower level floor.

During the next 30 s, the fire in the den had decreased, and by 420 s after ignition only small amounts of fire near the floor were visible. Firefighters began suppression through the open den window at 500 s after ignition. Table 5.9 provides a timeline of events.

Table 5.9: Timeline for Experiment 7, Den Fire with Front Door and Den Window Open

Time (s)	Event
0	Flaming ignition on the left side of upholstered chair seat
60	Flames beginning to heat gypsum board above and to the side of chair back
90	Light gray smoke flowing out of den doorway and window
90	Light smoke flowing into kitchen
120	Flames have extended 1 m above seat cushion, HGL developing in den approximately 0.6 m thick, smoke flow out of front doorway and window opening increasing
150	Smoke spreading across family room (upper level) ceiling
180	Flame involved in less than half of the chair initially ignited, HGL in the den 0.9 m thick.
220	Flames exiting the den doorway into lower level of structure, black smoke flowing out of the upper half of the den window
230	Smoke flow out of the open front door began
240	Ottoman in front of chair initially ignited is pyrolyzing
244	Hot gas layer in den starting to burn
255	Ottoman and adjacent sofa have ignited. Transition to flashover
270	Flames extending more than 2 m out of upper half of den doorway, flames have filled den window opening, window flames extended up the back of the structure to the second story, black smoke exhausting out of the front door opening top to bottom
300	Flames continue to flow out of the den doorway and open window, smoke layer in structure is within 0.5 m of the lower level floor
330	Fire has decreased in the den
420	Only small amounts of fire near the floor visible
500	Suppression started through open den window

Figure 5.61 provides the time history of the temperatures in the den. The temperature increase for the first 240 s was generated by the burning upholstered chair. Within 10 s, there were flames out of the doorway and the room transitioned to flashover, as seen by the temperature rise with floor to ceiling temperature of 880 °C (1616 °F). With sufficient fuel and ventilation (via the open front door and den window), the room was able to remain in a fully-developed start post-flashover until suppression 500 s after ignition. This is evident by the sharp drop in temperature starting at the 500 s mark.

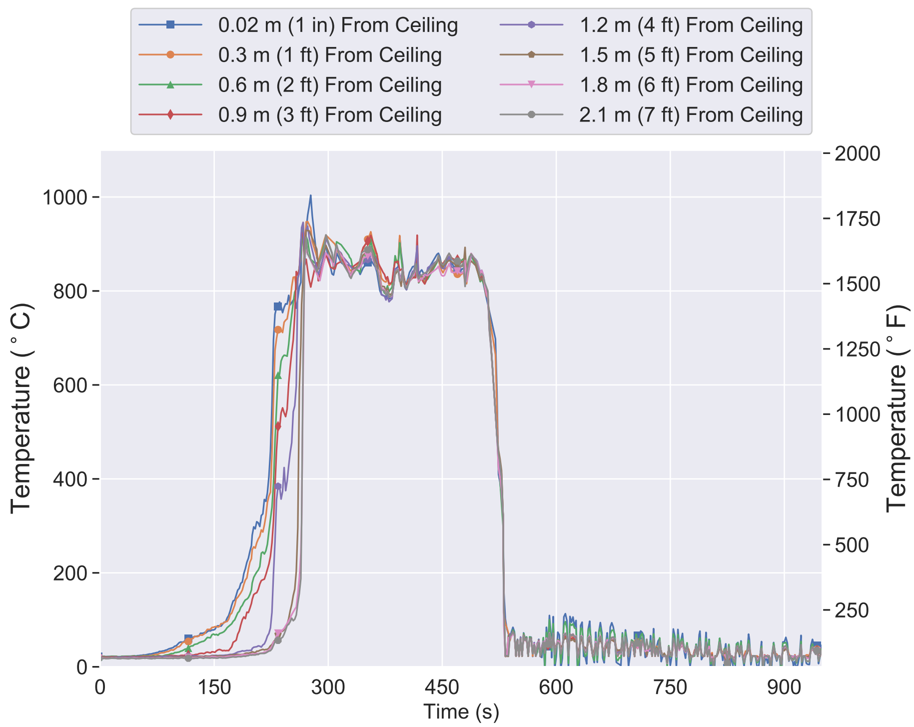


Figure 5.61: Experiment 7, front door and den window open, den temperatures versus time.

The front door was one of two exterior vents for this experiment. The temperatures measured in the front door opening appear in Figure 5.62. The main temperature increases were limited to the top third of the doorway. The elevated temperatures in the door show only a slight increase that began post-flashover and turned to decay following the suppression.

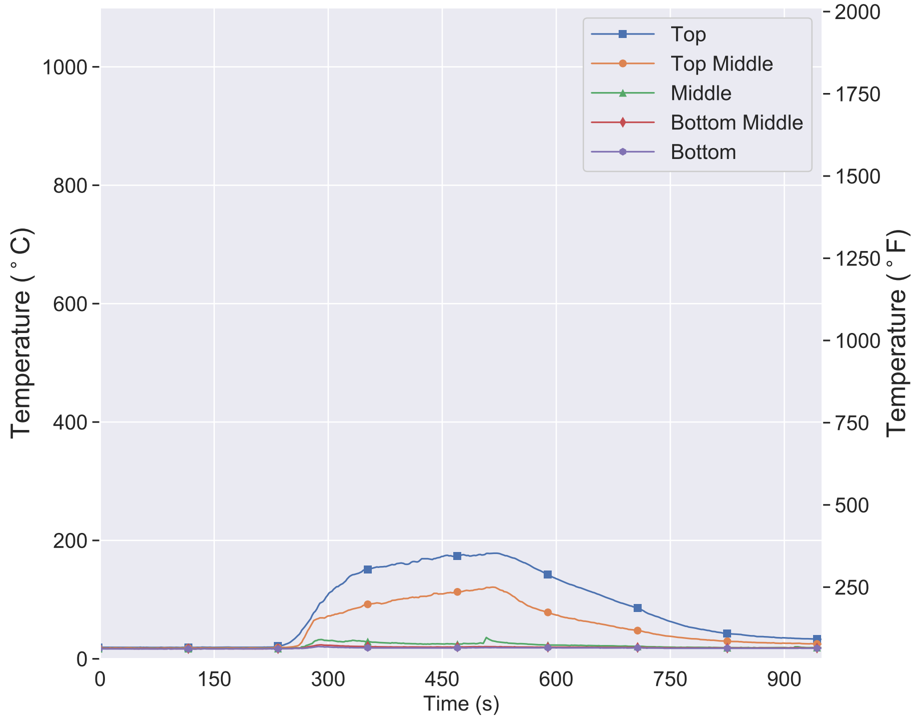


Figure 5.62: Experiment 7, front door and den window open, front door temperatures versus time.

The second exterior vent open was the den window. Because the den window was a fire room vent it resulted in higher temperatures compared the front door, which was remote from the fire. The top three thermocouples had temperatures in excess of 850 °C (1562 °F), which aligned with the visible flames from the window. Note that for approximately 45 s, the top two thermocouples lost signal, as shown by the gaps in the data stream. Figure 5.63 shows the den window temperature versus time.

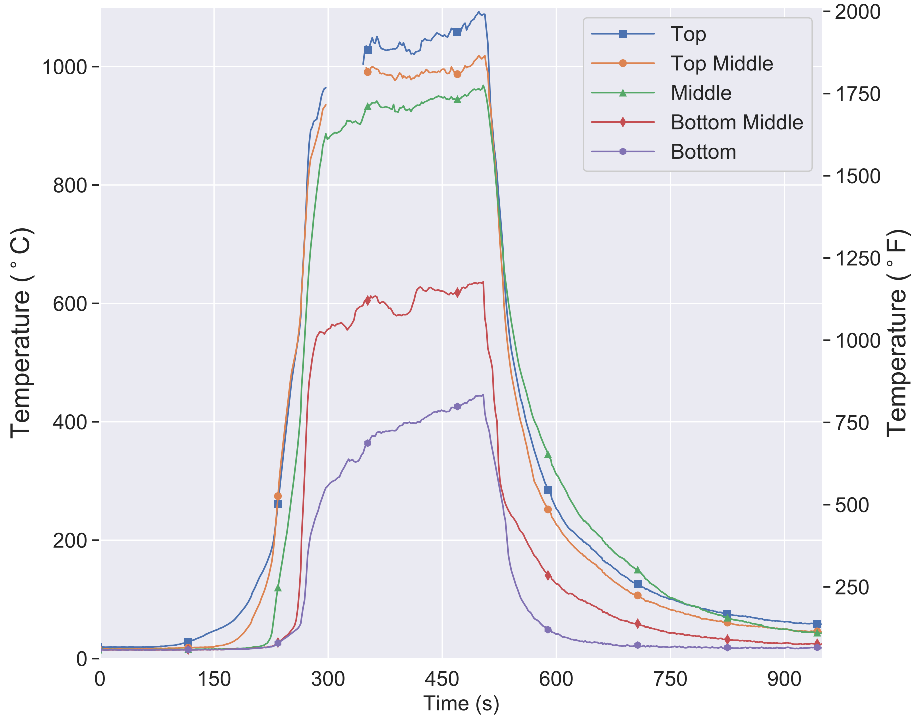
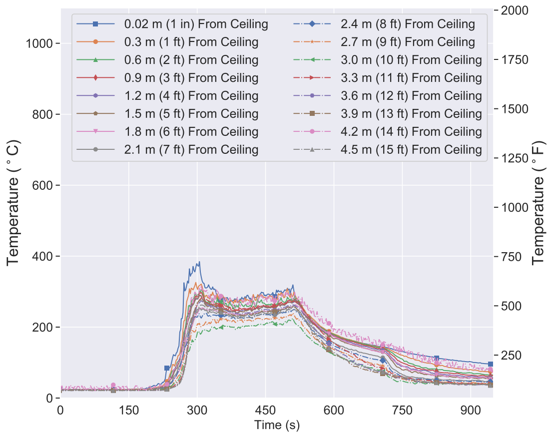


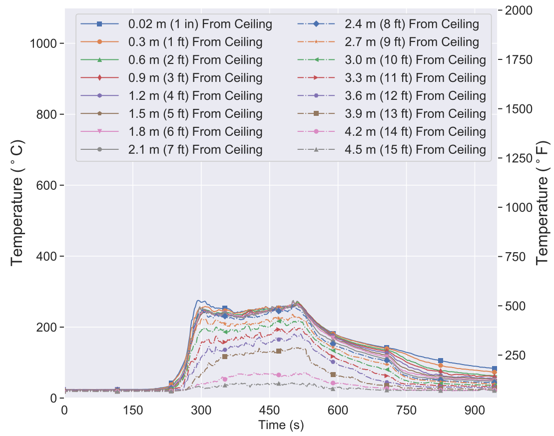
Figure 5.63: Experiment 7, front door and den window open, den window temperatures versus time.

Figure 5.64 contains six graphs with the temperatures from the thermocouple arrays that were located on the lower level. The five rooms open to fire room included from the closest to the den to the furthest: family room, dining room, foyer, and living room, and kitchen. The rooms in the flow path between the den and the front door were the kitchen, the family room, and the foyer. These three rooms had the highest peak temperatures outside of the laundry room.

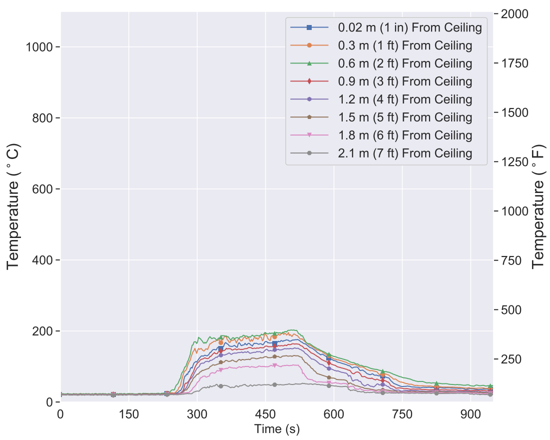
Along the flow path, the closer room (i.e., the family room) had the higher temperatures, while the further room (i.e. the foyer) had the lower temperatures. The dining room and kitchen room were outside of the flow path and had the lowest temperatures on the lower level. The living room, while not in the flow path, had elevated temperatures because of proximity to the den. Due to the open den window, the temperatures were not as high as compared to similar flow path arrays from the laundry room experiments, which did not have an open window.



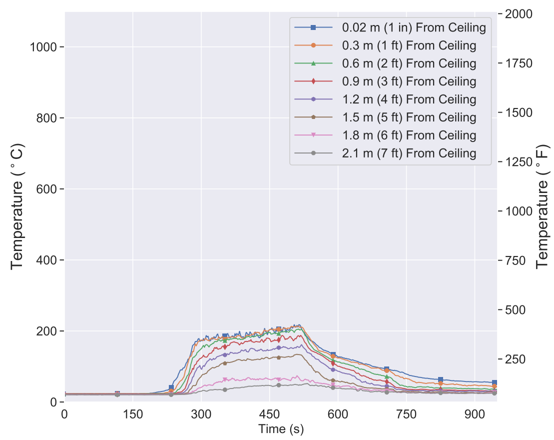
(a) Family Room Center Temperature



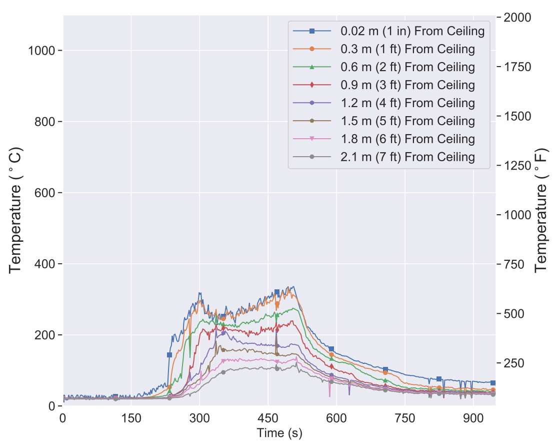
(b) Foyer Temperature



(c) Kitchen Temperature



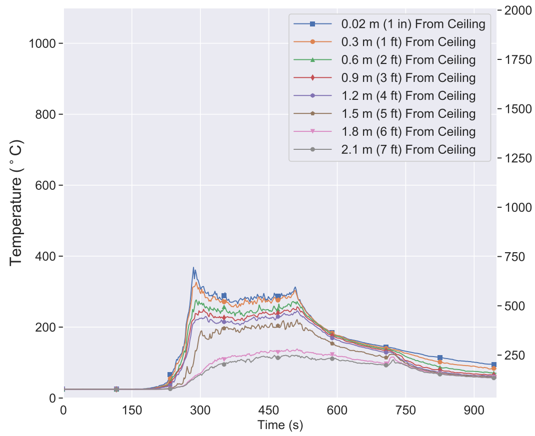
(d) Dining Room Temperature



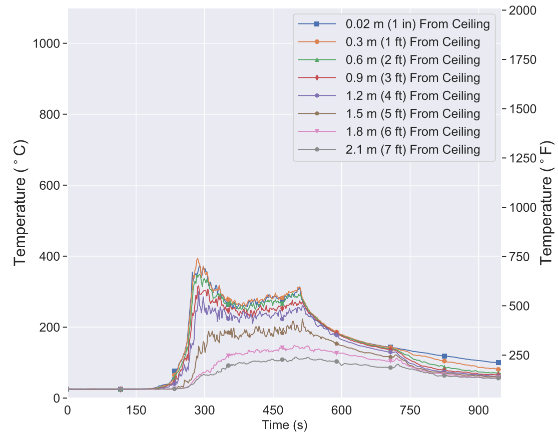
(e) Living Room Temperature

Figure 5.64: Experiment 7, front door and den window open, temperature time histories for first floor rooms

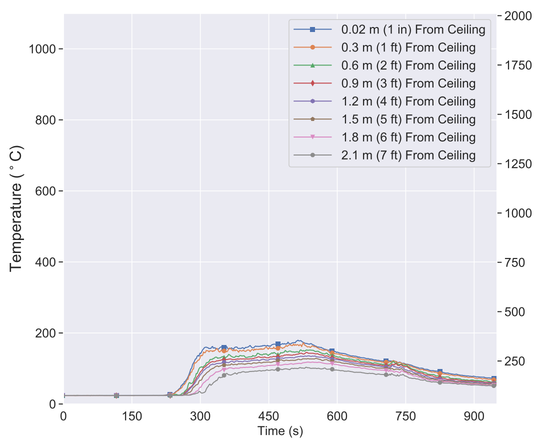
Figure 5.65 shows the temperatures recorded by the thermocouple arrays on the upper level. The hallway and bedroom 1 were open to the fire area. The mid-hall and end-hall array temperatures shown in Figures 5.65a and 5.65b had the most similar temperatures and trends as the temperatures in the family room. These arrays were in the exhaust flow of the hot gases as they flowed from the family room into the foyer and down toward the open front door. Bedroom 1 was not in the main upper level flow path and therefore had lower temperatures than the hallway arrays. Bedrooms 2, 3, and 4 were isolated from the fire area by having the doorways closed off, hence there was little to no increase in temperature in the bedrooms.



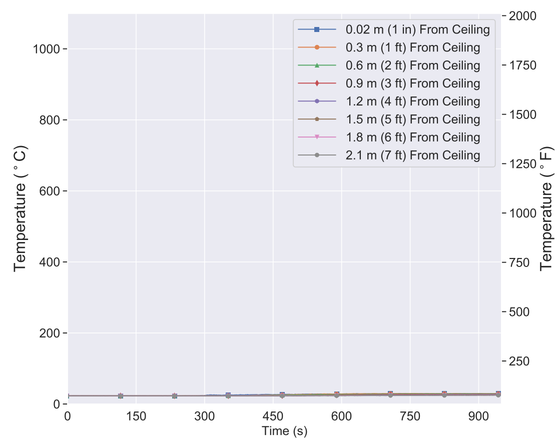
(a) Mid-Hall Temperature



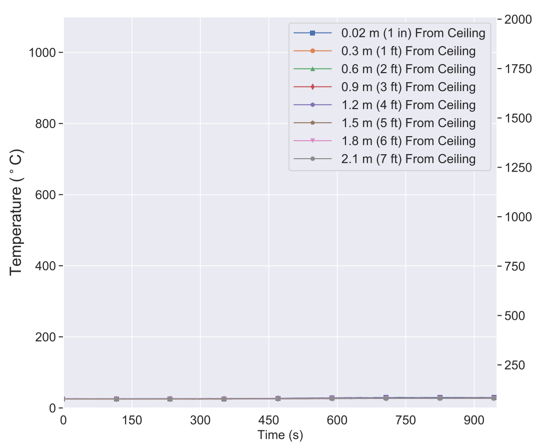
(b) End-Hall Temperature



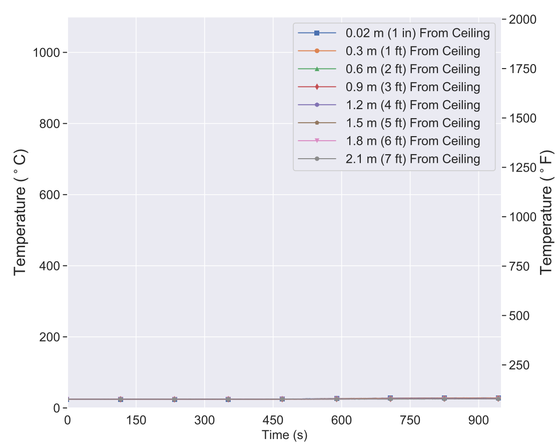
(c) Bedroom 1 Temperature



(d) Bedroom 2 Temperature



(e) Bedroom 3 Temperature

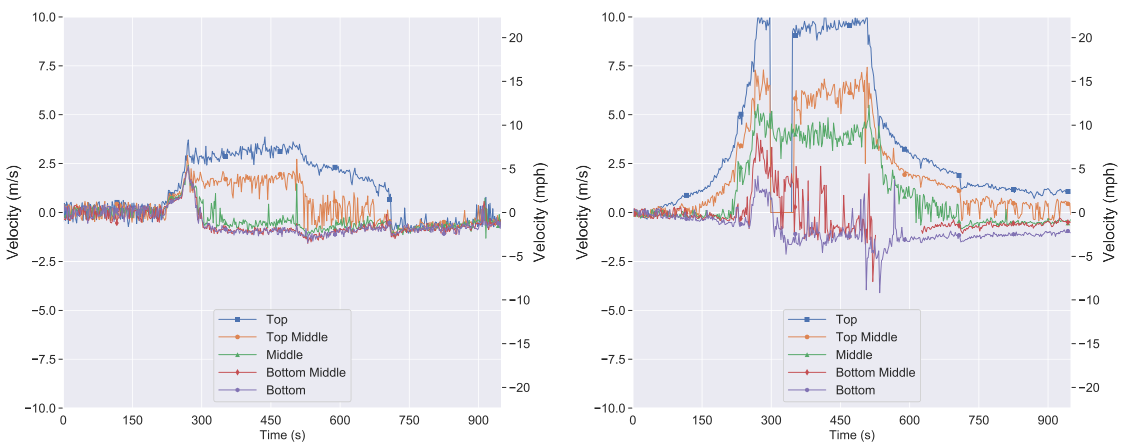


(f) Bedroom 4 Temperature

Figure 5.65: Experiment 7, front door and den window open, temperature time histories for second floor hallway and bedrooms.

Figure 5.66 provides the velocity profiles for both open exterior vents, the front door and den window, respectively. The increase in exhaust flow at both vents for the first 250 s tracks with the fire growth in the den. As the den transitioned to flashover, both vents were 100% exhaust. As the fire reached a fully-developed state, bi-directional flow was established at both vents to provide the necessary oxygen to sustain combustion. At the front door, only the top two probes were in the exhaust, peaking at 2.5 m/s (5.6 mph) at the top of the doorway, while the bottom three probes indicated intake. This was also reflected by the front door temperature profile (see Figure 5.62) where only the top two thermocouples measured a substantial rise in temperature.

The den window had higher velocities compared to the front door, primarily because of proximity to the source of the fire. The top of the window had peak exhaust flow of 10 m/s (22 mph), and the midpoint of the window was at 4.5 m/s (10 mph). The bottom two probes of the window became intakes to the room after the initial exhaust phase, with a steady flow of 1.4 m/s (3 mph). Note that the top two probes drop to zero over the same interval that their respective temperature sensors were lost. The velocity measurement depends on the local temperature, hence the temporary signal drop.



(a) Front Door Velocity

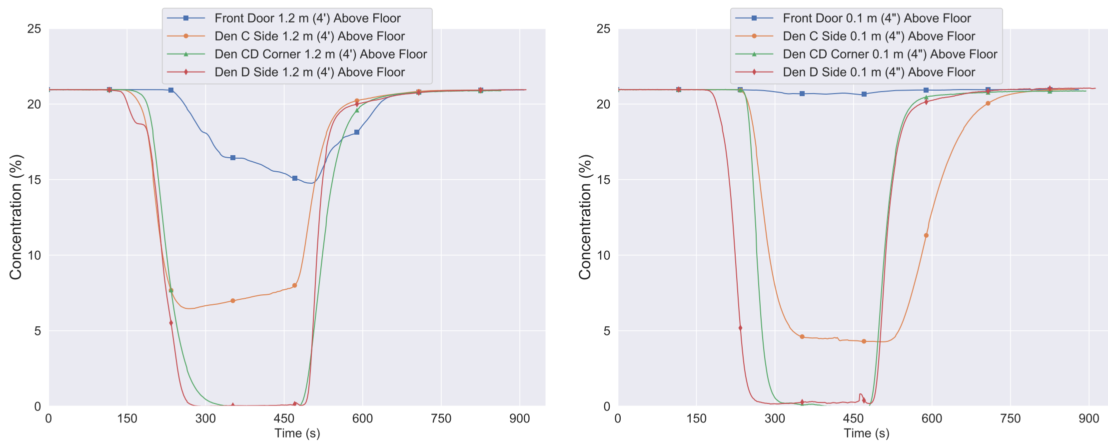
(b) Den Window Velocity

Figure 5.66: Experiment 7, front door and den window open, front door and den window velocity versus time.

The oxygen concentrations appear in Figure 5.67. Significant differences in oxygen concentration are shown based on the measurement location. The graph on the left (see Figure 5.67a) shows the oxygen concentrations at different positions 1.2 m (4 ft) above the floor. The graph on the right (see Figure 5.67b) shows the oxygen concentrations at different positions 0.1 m (4 in.) above the floor. Three of the oxygen concentration measurements were located within the den: along side D, along side D, and at the CD-corner. The fourth location was at the front door.

The oxygen concentrations measured within the den began to decrease as the smoke layer developed in the den and descended past the probes. The major drop in concentration occurred as the room transitioned to flashover, dropping the side C and CD-corner probes to 0%. This lack of oxygen within the compartment was also evident in the video analysis that showed flaming combustion at the den doorway and window post flashover. The side C probe did not drop as low as the other two locations within the den, minimum values of 6.4% and 4.4% for the 1.2 m (4 ft) and 0.1 m (4 in.) respectively. The probes were installed perpendicular to the open window through the exterior side C wall. The high speed flows out the window (see Figure 5.66b) could have impacted the sampling effectiveness at the location.

The front door oxygen sensor dropped to 15% at the 1.2 m (4 ft) level, which coincided with the layer height being approximately at the midpoint of the doorway. The 0.1 m (4 in.) location at the front door showed minimal change because the layer never descended that low.



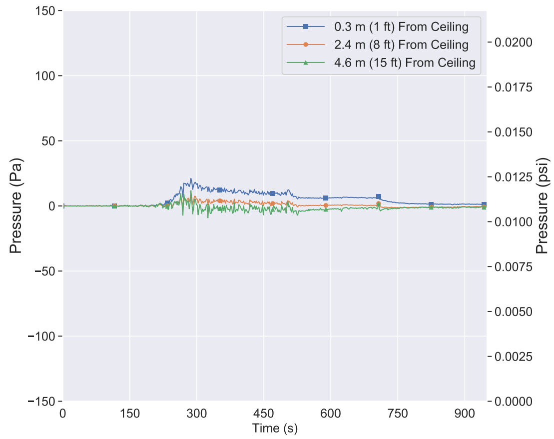
(a) Oxygen 1.2 m Above Floor

(b) Oxygen 0.1 m Above Floor

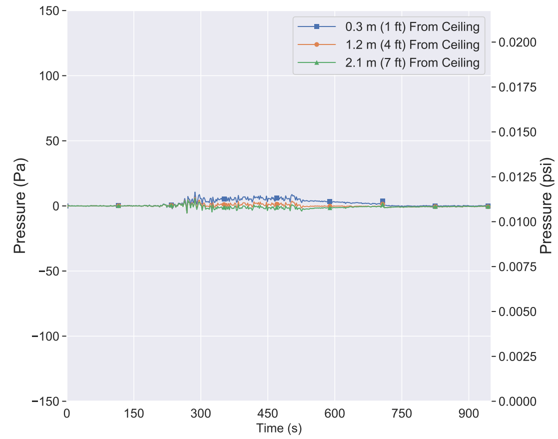
Figure 5.67: Experiment 7, front door and den window open, oxygen concentrations versus time.

Figure 5.68 shows the pressures from the rooms on the lower level outside of the den. The open front door acted as an exhaust (pressure relief) and intake vent. From the time of ignition, the trends of the pressures in the open lower level rooms were the same, with the den and family room (closest to the den) showing the highest pressure gradients. The pressure gradient in each room had the positive pressures near the ceiling and the negative pressures near the floor. As noted before, this pressure difference accounted for the circulation of hot gases out of the structure and air flow into the structure through the open front door.

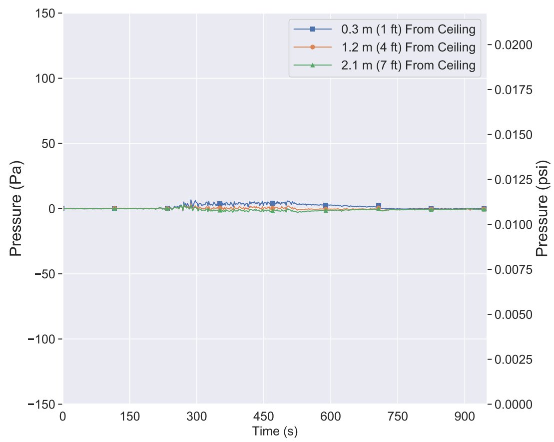
The pressure location near the ceiling in the family room had measurements of approximately 20 Pa, which were the highest pressure measurements in the structure during the post-flashover burning stage of the fire. The pressures in the upper level portion of the family room collected hot gases with no exhaust vent on the upper level, which in turn resulted in higher pressures than on the lower level of the structure.



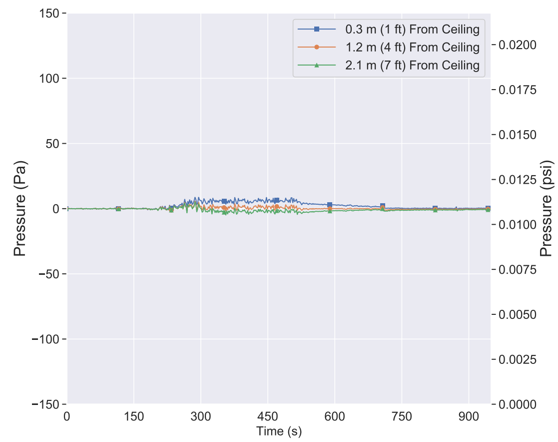
(a) Family Room Pressure



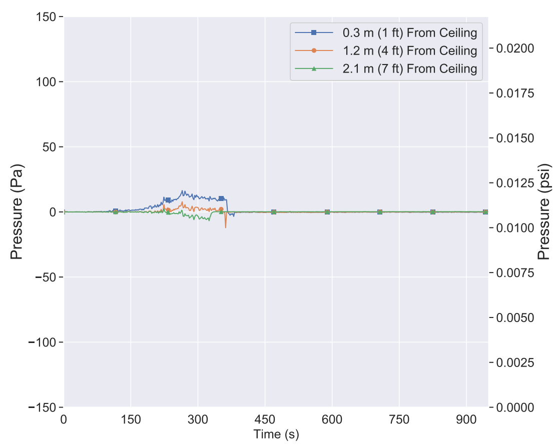
(b) Kitchen Pressure



(c) Front Door Pressure



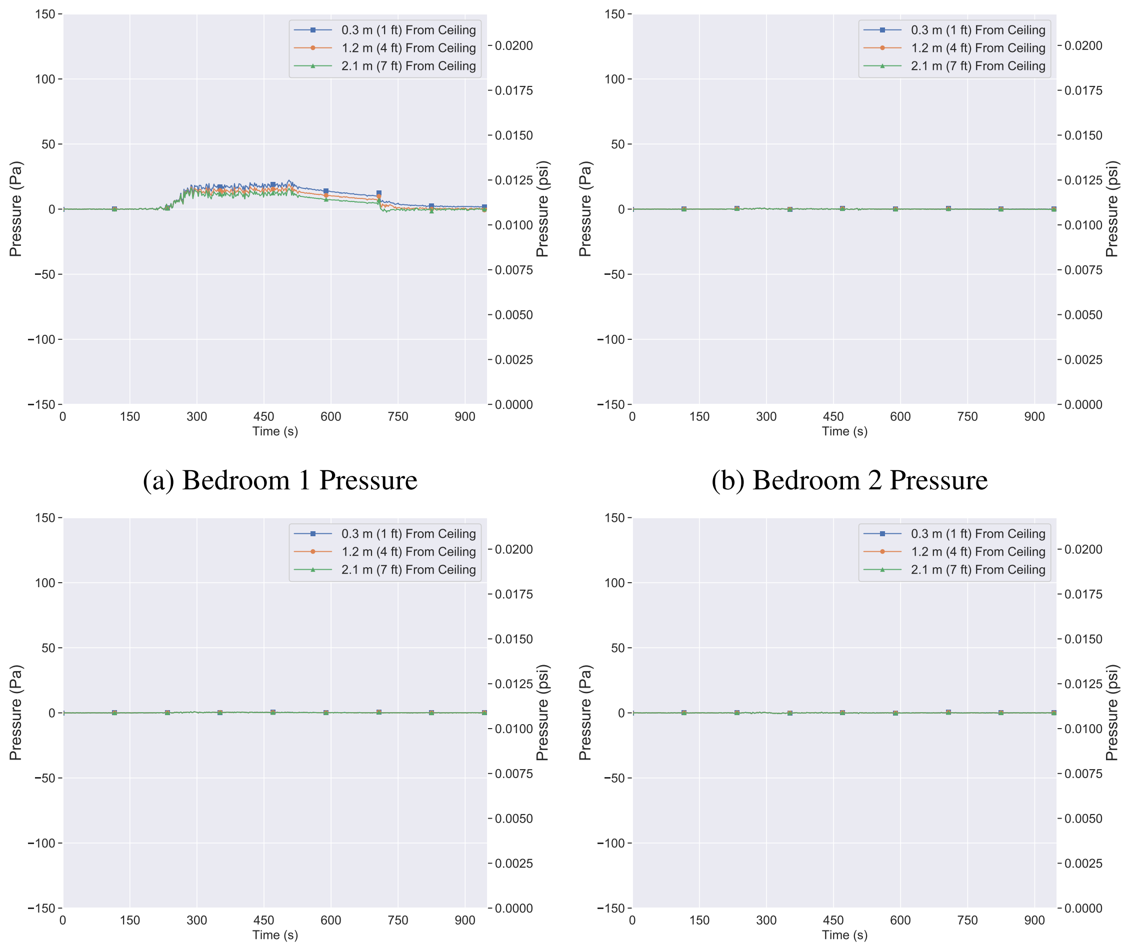
(d) Living Room Pressure



(e) Den Pressure

Figure 5.68: Experiment 7, front door and den window open, pressures in first floor rooms.

The pressures on the upper level appear in Figure 5.69. Bedroom 1 was the only room open to the fire area. The pressure trends in bedroom 1 are similar to the pressure in the upper portion of the family room. Bedroom 1 had a positive pressure from fire growth through suppression and ventilation because there was no exhaust vent on the upper level and bedroom 1 was located above the neutral plane. The pressures in bedroom 1 spiked as a result of the front door closure in concert with the pressures throughout the structure. Bedrooms 2, 3, and 4 were closed off from the fire area, which resulted in little to no pressure change within those bedrooms.



(a) Bedroom 1 Pressure

(b) Bedroom 2 Pressure

(c) Bedroom 3 Pressure

(d) Bedroom 4 Pressure

Figure 5.69: Experiment 7, front door and den window open, pressures in second floor rooms.

6 Discussion

The discussion of the experimental results is divided into two sections: repeatability and impact of ventilation. In the repeatability section, key data elements for each of the single story structure experiments with a similar area of origin and similar ventilation conditions are presented for comparison. The impact of ventilation section compares key data elements of both single story and two story structure experiments that had the same room of fire origin but different ventilation configurations. Throughout both sections, the correlation between temperatures and oxygen consumption inside the structure has been considered.

6.1 Repeatability

The single story, ranch-style structure was used for all of the replicate experiments. Over the course of 12 experiments, three different rooms were used as the area of origin, and two different ventilation configurations were used in each room. Two experiments were conducted for each combination of area of origin and ventilation configuration.

One of the first items to address is, do comparisons of these experiments provide the precision of repeatability or reproducibility? According to ASTM E177-14, repeatability is a measure of precision determined from multiple test results conducted under repeatability conditions. Repeatability conditions are provided as a test method conducted by a single well-trained operator using one set of equipment in a short period of time during which neither the equipment nor the environment is likely to change appreciably. Reproducibility is a measure of precision determined from multiple test results conducted under reproducibility conditions. Reproducibility conditions are provided as a test method conducted in several laboratories, each with its own operator, apparatus, and environment conditions [38].

The definitions seem to address a well defined test apparatus. For our experiments, the test apparatus consisted of an instrumented structure. The experiments were conducted by the same team, the experiments were all conducted in the same laboratory, and the experiments were conducted over a six week period. While these experiments may be beyond the strict definition of repeatability conditions, it would seem that repeatability is the more appropriate term to use in these comparisons.

The similarity between the experiments will be noted based on the total expanded uncertainty associated with the individual measurements. For example, the total expanded uncertainty associated with the temperature measurements from these experiments is estimated to be $\pm$ 15%, and the similar value for the oxygen concentration is $\pm$ 12%.

6.1.1 Living Room Fires

The living room was the room of origin for two experiments with all of the exterior vents closed, and for two experiments with the front door open. Looking in from the front door toward the hallway to the bedrooms, the sofa against the wall to the right of the hallway was the first item ignited in each of these experiments (see Figure 3.18). The point of ignition was the left side of the sof, at the intersection of the seat cushion, the arm rest, and the back cushion.

All Exterior Vents Closed

Ranch Experiments 1 and 2 had all of the exterior doors and windows closed. The sofa fire grew to the point of generating flashover conditions within a portion of the living room. The flashover was supported by oxygen contained within the structure. Post-flashover, the flaming combustion decreased rapidly, and the temperatures throughout the structure began to decrease as a result of reduced levels of oxygen within the structure.

Figures 6.1 and 6.2 provide a graphic representation of the flow paths within the ranch structure. Figure 6.1 shows the flow of hot gases (red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure that are open to the living room. As the hotter, higher pressure fire gases flow into other rooms, such as the kitchen, dining room, or bedroom 2, the fresh air (green arrows) in those rooms was displaced toward the area of origin. This delivered oxygen needed for combustion. As combustion within the structure ceased due to a lack of oxygen, the measurable flows also stopped, as represented by the smoke-filled areas in Figure 6.2. Bedrooms 1 and 3 are closed and are not part of the flow paths.

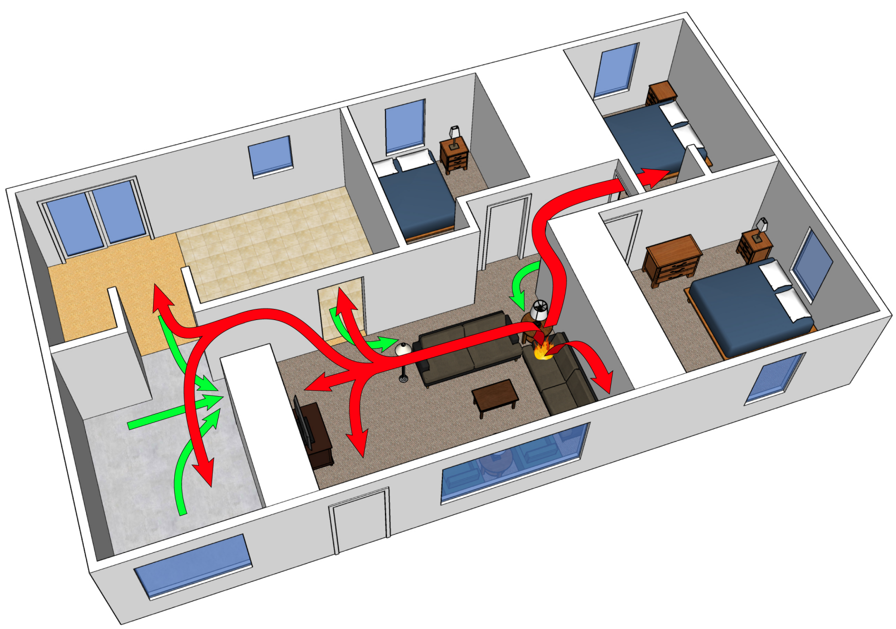
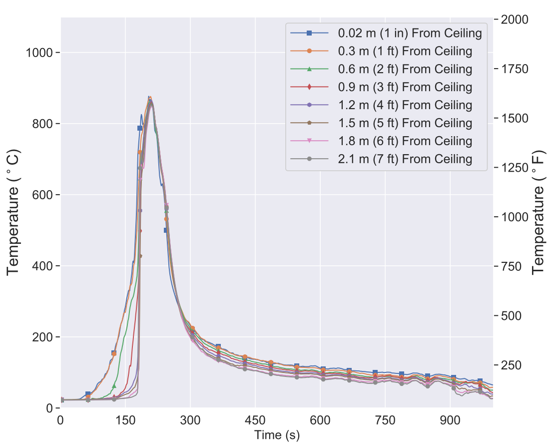


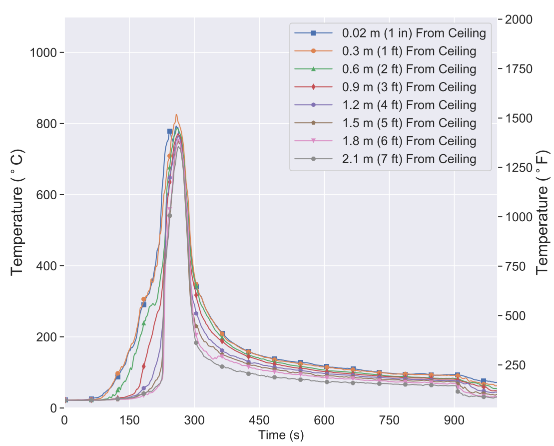
Figure 6.1: Drawing of the pre-flashover flows within the closed ranch structure, living room fire.

Figure 6.2: Drawing of the post-flashover conditions within the closed ranch structure, living room fire.

The temperature time histories of the living room fires were similar in magnitude as shown in Figure 6.3. The time to flashover was slower in Experiment 2. This time difference was attributed to the initial growth rate of the fire immediately after ignition.



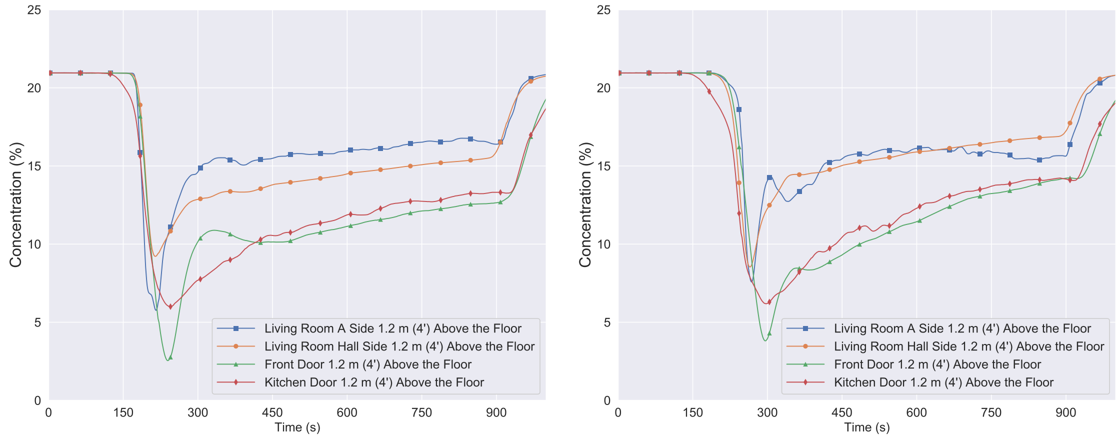
(a) Experiment 1



(b) Experiment 2

Figure 6.3: Comparison of closed door living room fire temperatures.

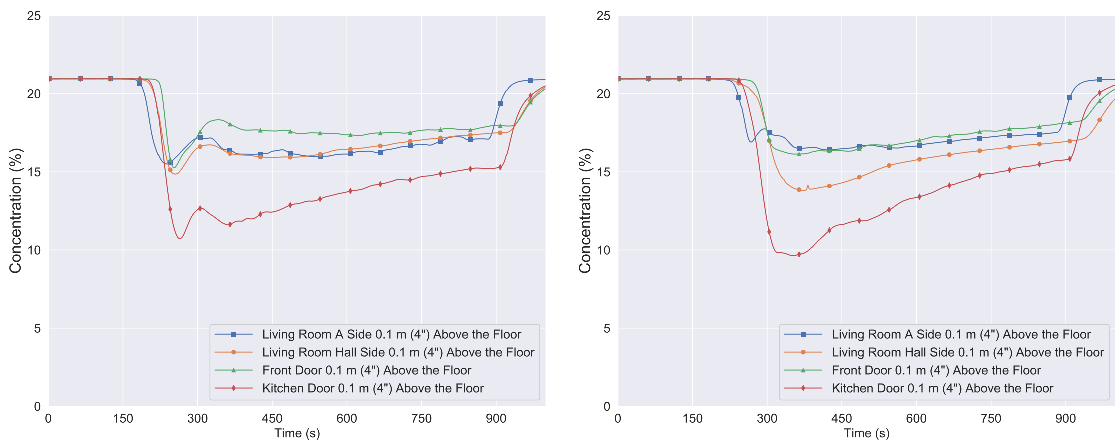
In both experiments post-flashover, the oxygen levels measured at 1.2 m above the floor around the living room decreased to 10% or less shown in Figure 6.4. The oxygen levels measured at 0.1 m above the floor decreased to 17% or less as shown for both experiments in Figure 6.5. While each of the oxygen concentration values are not exact matches, the trends are similar, and the relationship between oxygen values and the increase and decrease in temperatures in the living room are consistent.



(a) Experiment 1

(b) Experiment 2

Figure 6.4: Comparison of closed door oxygen concentrations at 1.2 m above the floor for living room fire.



(a) Experiment 1

(b) Experiment 2

Figure 6.5: Comparison of closed door oxygen concentrations at 0.1 m above the floor for living room fire.

Fire Damage Comparisons

From a data perspective, the time histories provide a sense of similar fire behavior in terms of trends and magnitudes. Of course, in an actual incident the fire investigator would not have access to data sets like this to determine how the fire of interest was burning and the area of origin. In an actual fire investigation, the fire patterns could be one of the key elements that would be analyzed to determine the area of origin. Therefore, connecting the fire damage that occurred in these experiments provides a connection to the data and reference points for fire investigators.

Figures 6.6 through 6.9 compare similar photographs of the two living room fires conducted with no open exterior vents.

The post fire suppression photographs of the living room looking toward the area of origin (see Figures 6.6 and 6.7) have many similarities. The wall behind the ignition sofa and the floor area under the sofa have fire damage patterns that frame the point of origin. Both walls have a vertical damage pattern starting above the back of the sofa and continuing toward the ceiling. The line of demarcation on the left wall was horizontal and approximately 1.5 m (5 ft) above the floor in both experiments.

Examining the furniture, the ignition sofa has the most fire damage. Moving away from the point of ignition toward the front door, the thermal damage to the furniture decreased. The wood moulding surrounding the living room window opening sustained the most fire damage on the vertical piece on the side of the window closest to ignition. The top piece of moulding above the window was charred close to the point of origin, and the damage decreased moving away from the origin. The vertical wood moulding closest to the front door had no thermal damage. The baseboard moulding along the floor was undamaged with the exception of the moulding behind the ignition sofa. The extent of the damage to the moulding behind sofa was similar.

(a) Experiment 1 (b) Experiment 2

Figure 6.6: Post-suppression comparison of living room area of origin, with closed door.

(a) Experiment 1 (b) Experiment 2

Figure 6.7: Post-overhaul comparison of living room area of origin, with closed door.

Figures 6.8 and 6.9 show the area adjacent to the front door. There is limited soot damage on the wall. It would appear that the exposed portion of the wall was heated enough that only a limited amount of soot condensed on the exposed portion of the wall. The portion of the wall behind the TV stand was shielded from the radiant heat from the fire and was at a lower temperature than the rest of the wall. The smoke convected behind the TV stand came in contact with the cool portion of the wall, and some of the soot condensed out on the wall behind the TV stand. Also note that the carpeting on this side of the room sustained no thermal damage in both cases.

(a) Experiment 1 (b) Experiment 2

Figure 6.8: Post-suppression comparison of living room wall opposite the area of origin and adjacent to front door with closed door.

(a) Experiment 1 (b) Experiment 2

Figure 6.9: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with closed door.

Key differences between the two experiments included the damage to the ceiling, damage to the moulding on the bottom of the window, and damage to the carpeting. The damage to the ceiling was more extensive in Experiment 1 than Experiment 2, although the thermal damage did not extend all the way across the ceiling. In Experiment 1, the piece of moulding on the bottom of the window had burn damage that extended behind the chair closest to the point of ignition before it stopped. In Experiment 2, there was no fire damage on this piece of moulding. In Experiment 1, there was more fire damage to the carpeting in the area between the chairs and the sofas than in Experiment 2. This larger area of damage on the floor is consistent with the larger area of damage on the ceiling in Experiment 1.

Front Door Open

Experiments 3 and 4 in the single story had all of the exterior doors and windows closed except for the open front door. The sofa fire grew to the point of generating flashover conditions within a portion of the living room. The flashover was supported by oxygen contained within the structure and flow through the front door. Post-flashover, the flaming combustion was sustained by the influx of air through the doorway, and the temperatures throughout the structure remained elevated until suppression.

Figures 6.10 and 6.11 provide a graphic representation of the flow paths within the ranch structure. Figure 6.10 shows the flow of hot gases (red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure that are open to the living room. As the hotter, higher pressure fire gases flow into other rooms, such as the kitchen, dining room, bedroom 2, or out of the front door, the fresh air (green arrows) in those rooms was displaced toward the area of origin. This represents the availability of oxygen needed for flashover. Post-flashover, the measurable air flow within the structure was minimal. Post-flashover the air was supplied primarily through the front door and flowed to the area of combustion which had moved from the area of origin toward the doorway. The remainder of flow movement within the structure was the circulation of combustion products, as represented by the predominant red arrows in Figure 6.11. Bedrooms 1 and 3 are closed and are not part of the flow paths.

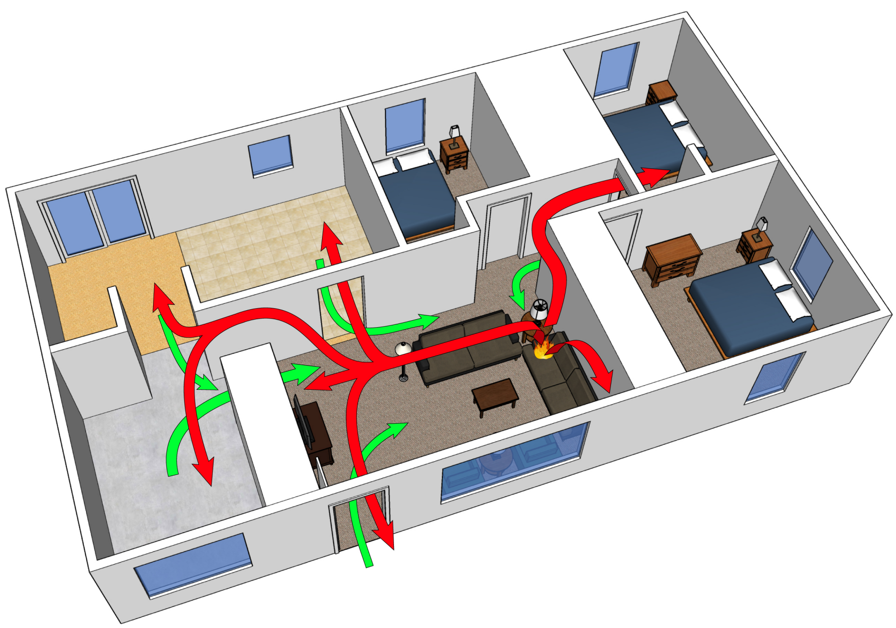


Figure 6.10: Drawing of the pre-flashover flows within the ranch structure, living room fire with open front door.

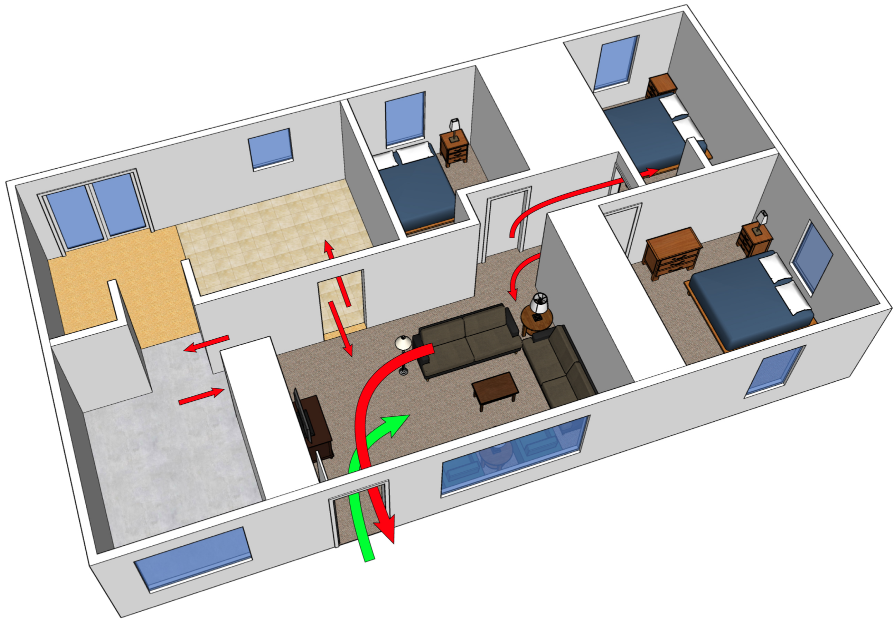
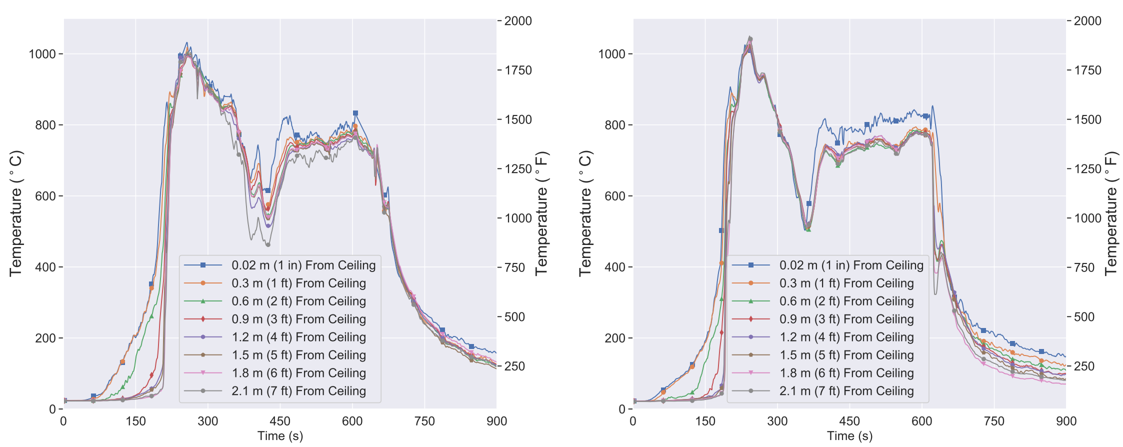


Figure 6.11: Drawing of the post-flashover flows within the ranch structure, living room fire with open front door.

The temperature time histories of the living room fires were similar in magnitude as shown in Figure 6.12. The growth rate, time to flashover, and post-flashover behavior were similar for both experiments. Experiment 4 showed a sharper decay, likely due to more efficient suppression actions.

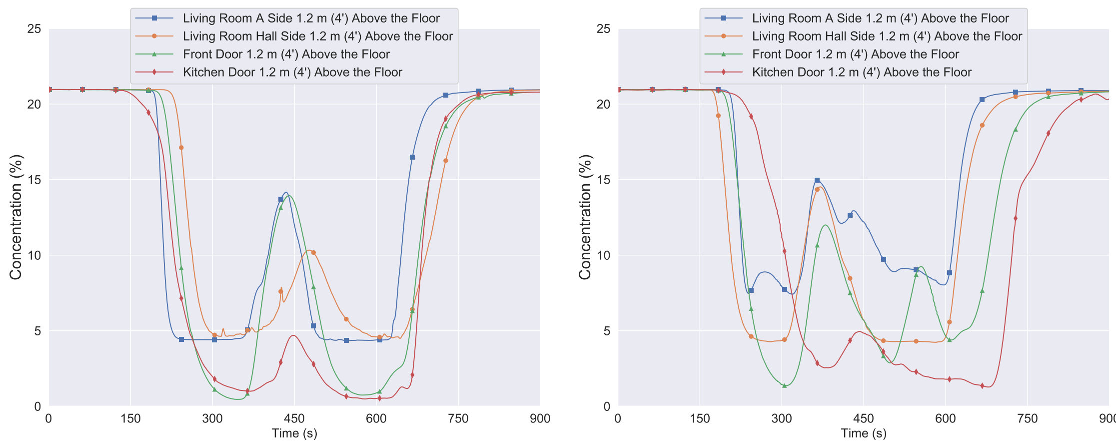


(a) Experiment 3

(b) Experiment 4

Figure 6.12: Comparison of open door living room fire temperatures.

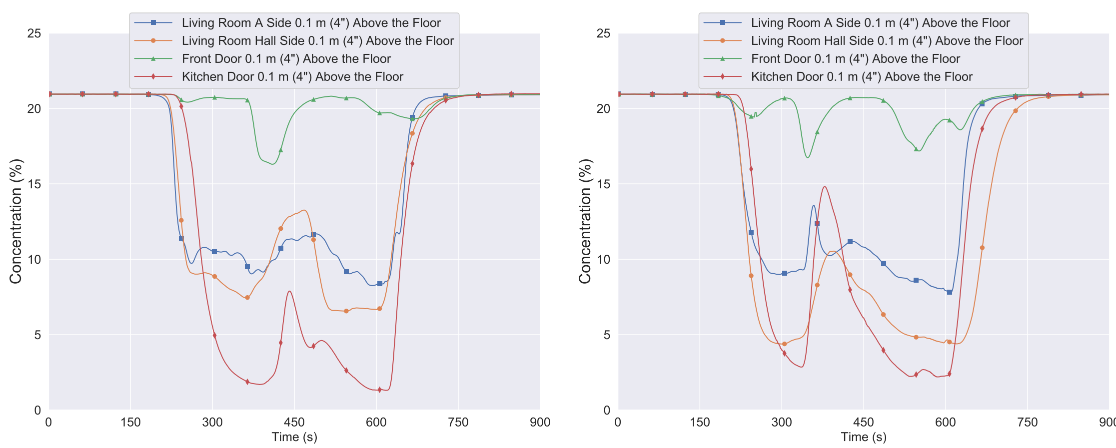
In both experiments post-flashover, the oxygen levels measured at 1.2 m above the floor located around the living room decreased to 5%–8% as shown in Figure 6.13, recovered to approximately 15% as the fire decayed, and again dropped to 5%–8% as the fire recovered. The oxygen levels measured at 0.1 m above the floor (see Figure 6.14) showed a similar trend for the living room and kitchen; there was a decay to between 5%–10%, a recovery, and then a second decay before a full recovery following suppression. The front door did not see as significant of decay in either experiment as the door fluctuated between exhaust and intake. While each of the oxygen concentration values are not exact matches, the trends are similar, and the relationship between oxygen values and the increase and decrease in temperatures in the living room were consistent.



(a) Experiment 3

(b) Experiment 4

Figure 6.13: Comparison of open door oxygen concentrations at 1.2 m above the floor.



(a) Experiment 3

(b) Experiment 4

Figure 6.14: Comparison of open door oxygen concentrations at 0.1 m above the floor.

Fire Damage Comparisons

Figures 6.15 and 6.18 show the post fire suppression photographs of the living rooms that burned with the front door open. Both rooms burned for approximately 7 min post-flashover.

The first two sets of photographs are of the area of origin (see Figures 6.15 and 6.16). These two living rooms have many similarities. The wall behind the ignition sofa and the floor area under the sofa have fire damage patterns above and below the outline of the sofa that frame the point of origin. Both walls have a vertical damage pattern starting above the back of the sofa and continuing toward the ceiling.

Both of the ceilings have had most of face paper of the gypsum board burned off over the full length and width of the living room. The carpet and padding burned with the exception of some small protected areas, such as areas under a solid object like the base of the floor lamp or the TV stand. The sub-floor was charred from the ignition wall to the front door, and from the second sofa to the front wall. The horizontal line of demarcation on the left wall was approximately 0.75 m (2.5 ft) above the floor in both experiments.

(a) Experiment 3 (b) Experiment 4

Figure 6.15: Post-suppression comparison of living room area of origin, with open door.

(a) Experiment 3 (b) Experiment 4

Figure 6.16: Post-overhaul comparison of living room area of origin, with open door.

All of the upholstered furniture burned to the wood frame, which was charred. There was no directionality to the fire damage of the furniture, unlike the first two experiments. All four sides of the wood moulding surrounding the living room window opening were charred. The exposed moulding around the front door was also charred. The moulding on the hinge side of the door had less damage along the lower half of the door than the rest of the door moulding. The baseboard moulding along the floor under the window was charred along the full length, except where it was protected by a chair or toward the corner near the ignition sofa. The baseboard moulding along the left wall was undamaged, and the baseboard on the ignition wall and the TV wall only had charring in the area behind the sofa or behind the TV stand.

Figures 6.17 and 6.18 show the area adjacent to the front door. Both of the walls show a dark pattern on the wall in the area of the TV stand. There is an area in the center of each pattern that has additional burn damage, some portions of it clean burned. On the right side of each of the patterns is a dark plume mark that sweeps over and up the right side. This collection of damage was likely caused by the intake air from the door, which enabled the TV stand to burn later into the fire event, resulting in a clean burn in the middle of a pre-flashover soot pattern. The flow of the intake air caused the combustion products from the burning TV stand to flow toward the inside of the house. If the outward plume pattern was caused by an obstruction and not impacted by the ventilation, two equal plumes on both sides of the TV stand would be expected.

(a) Experiment 3 (b) Experiment 4

Figure 6.17: Post-suppression comparison of living room wall opposite the area of origin and adjacent to front door with open door.

(a) Experiment 3 (b) Experiment 4

Figure 6.18: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with open door.

Based on the observations and looking at the various surfaces and target fuel material that was positioned around the living room, there were no major differences. Basically, both rooms were consistent with post-flashover burning and had similar, not identical, but similar damage patterns.

6.1.2 Kitchen Fires

The kitchen was the room of origin for two experiments with all of the exterior vents closed and for two experiments with the front door open. Looking into the kitchen from the living room, the fire was ignited in each of these experiments at the coffee pot in the right hand corner on top of the counter (see Figure 3.19).

All Exterior Vents Closed

Ranch Experiments 3 and 4 had all of the exterior doors and windows closed. The kitchen grew to the point of approaching flashover conditions within the kitchen, but there was insufficient oxygen to flash over the room. After reaching a peak approximately 450 s post ignition, the flaming combustion decreased rapidly and the temperatures throughout the structure began to decrease as a result of reduced levels of oxygen within the structure.

Figures 6.19 and 6.20 provide a graphic representation of the flow paths within the ranch structure. Figure 6.19 shows the flow of hot gases (red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure that are open to the kitchen. As the hotter, higher pressure fire gases flowed into other rooms such as the breakfast area, dining room, or bedroom 2, the fresh air (green arrows) in those rooms was displaced toward the area of origin. This delivered the supply of oxygen needed for combustion. As combustion with in the structure ceased due to a lack of oxygen, the measurable flows also stopped, as represented by the smoke-filled areas in Figure 6.20. Bedrooms 1 and 3 are closed and are not part of the flow paths.

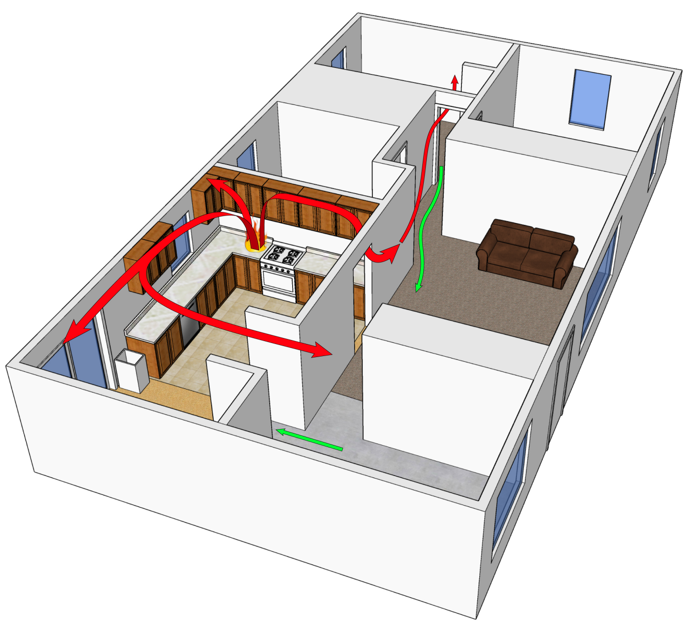


Figure 6.19: Drawing of the pre-flashover flows within the closed ranch structure, kitchen fire.

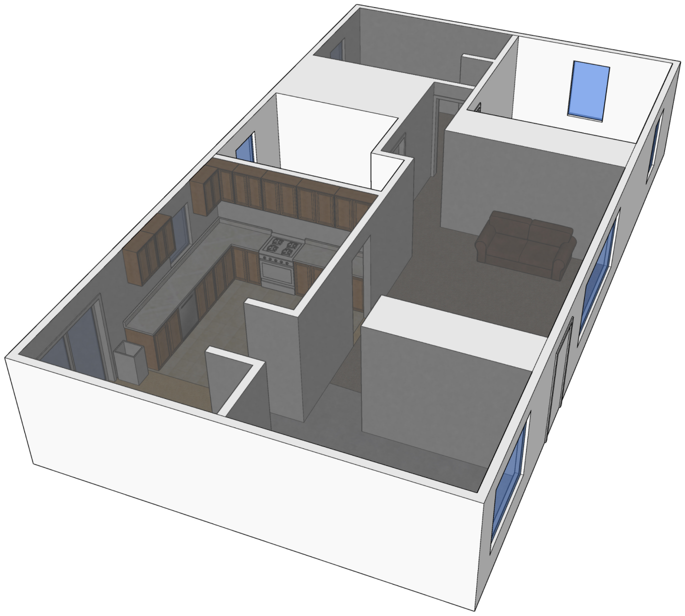
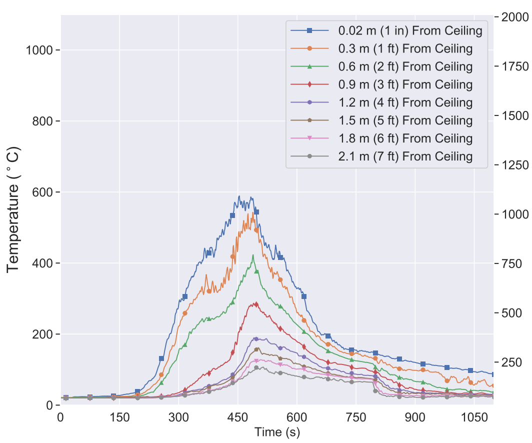
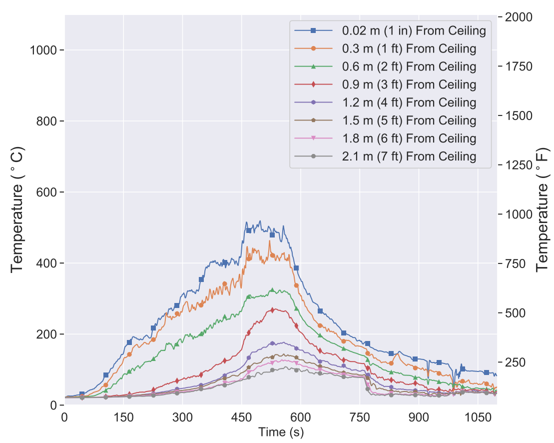


Figure 6.20: Drawing of the post-flashover condition within the closed ranch structure, kitchen fire.

For the closed door kitchen fires, the thermocouple array in the kitchen for Experiment 8 failed during the experiment. To compare these experiments, the breakfast area temperatures are used because the breakfast area is the next closest measurement array to the kitchen. The temperature time histories of the kitchen fires were similar in magnitude as shown in Figure 6.21, but lower in overall magnitude compared to the kitchen.



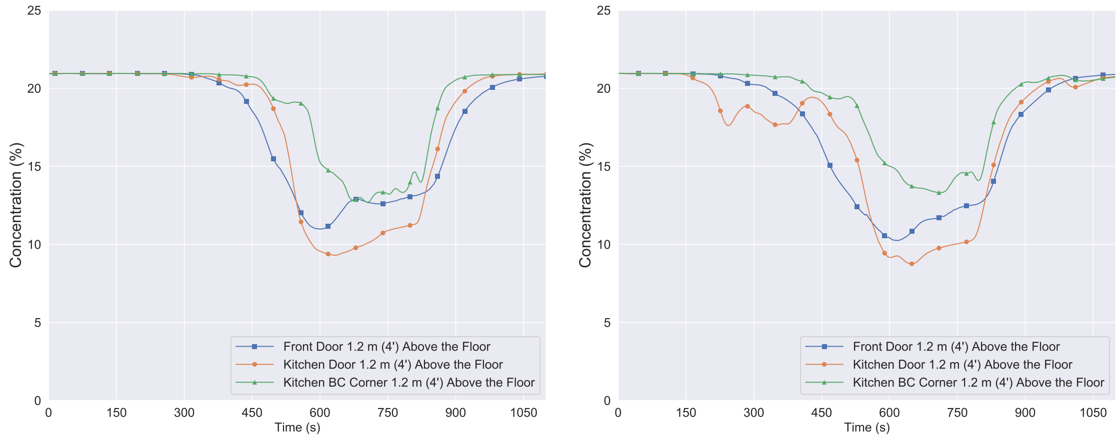
(a) Experiment 6



(b) Experiment 8

Figure 6.21: Comparison of closed door breakfast area temperatures.

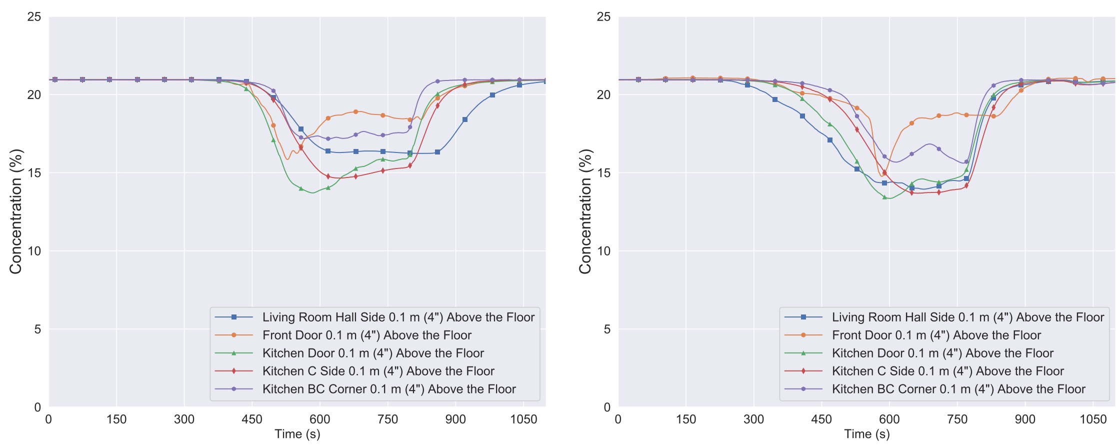
In both experiments post-flashover, the oxygen concentrations measured at three locations 1.2 m above the floor in the kitchen and the front door decreased to a range of 9%–13% as shown Figure 6.22. The oxygen concentrations measured at five locations 0.1 m above the floor decreased to between 14%–18% as shown for both experiments in Figure 6.23. While each of the oxygen concentration values between the experiments are not exact matches, the trends are similar, and the relationship between oxygen values and the increase and decrease in temperatures in the living room were consistent.



(a) Experiment 6

(b) Experiment 8

Figure 6.22: Comparison of closed door oxygen concentrations at 1.2 m above the floor for kitchen fire.



(a) Experiment 6

(b) Experiment 8

Figure 6.23: Comparison of closed door oxygen concentrations at 0.1 m above the floor for kitchen fire.

Fire Damage Comparison

Figures 6.24 and 6.25 show the post fire suppression photographs of the kitchen fire experiments that burned with no exterior vents open. Both rooms burned until they self-extinguished. The fire in Experiment 6 appeared to self extinguish about 8 min and 30 s after flaming ignition of the coffee maker. The fire in Experiment 8 appeared to self-extinguish at 10 min and 45 s after ignition of the coffee maker. In both experiments, firefighters entered the structure approximately 13 min after ignition and extinguished hot spots with a handheld fire extinguisher.

The walls behind the ignition area have similar flow patterns from the coffee maker up and around the bottom of the wall cabinet. Moving to the right, the line of demarcation flows across the front of the wall cabinets on the other side of the range. The doors on the small cabinet over the range had burned through in both fires.

The wall cabinets above ignition have different levels of damage. Both were fully involved in the fire and the cabinet doors burned away, as did the fuel load inside the cabinet. However, in Experiment 6, the outer box of the cabinet was still on the wall, while in Experiment 8, only the back board of the cabinet was attached to the wall. When the wall cabinet collapsed, that removed an obstruction to the fire burning up from the counter. Without the cabinet in the way, the flames extended toward the ceiling, which resulted in the ceiling damage aligned with the point of origin and toward the center of the room. Since much of the heat went up and away from the countertop area of origin, the damage to the cabinet on the left wall adjacent to the fire origin was reduced when compared to Experiment 6. In Experiment 6, the bottom of the wall cabinet over the coffee maker remained in place, which directed flames toward the bottom of the cabinet on the left wall. This resulted in additional burning of the wall cabinet on the left wall, which in turn caused more thermal damage to the ceiling toward the left wall.

Moving past the window on the left wall, the damage of both experiments becomes more alike. There was no thermal damage on either dinette set. Further, the plywood floor was undamaged in both experiments.

(a) Experiment 6 (b) Experiment 8

Figure 6.24: Post-suppression comparison of kitchen room area of origin with a closed door.

(a) Experiment 6 (b) Experiment 8

Figure 6.25: Post-suppression comparison of kitchen dining area opposite area of origin with closed door.

The next pairs of figures show the post fire conditions in the living room. Figure 6.26 shows the area between the closed front door on the left and the open doorway to the kitchen on the right. In both experiments, there is evidence of smoke flow through the upper portion of the kitchen doorway with soot deposited above the doorway, on both sides of the door, and spread over the living room ceiling. The photos in Figure 6.27 show the sofa located on the wall opposite the wall with the bookcase. There was no thermal damage to that wall or the sofa in either experiment.

There were differences within the pre-flashover damage zone due to the timing of the cabinet collapse. Considering the fires from the aspect of ventilation and available oxygen for combustion, these fires and the resulting damage were very similar. The fire damage was limited to the corner of the kitchen near the fire origin, and then the flaming combustion self-extinguished and did not re-kindle.

(a) Experiment 6 (b) Experiment 8

Figure 6.26: Post-suppression comparison of kitchen room area of origin and closed door.

(a) Experiment 6 (b) Experiment 8

Figure 6.27: Post-suppression comparison of living room wall remote from kitchen with closed door.

Front Door Open

Ranch Experiments 10 and 11 had all of the exterior doors and windows closed except for the open front door. The kitchen fire grew to the point of generating flashover conditions within the kitchen. The flashover was supported by oxygen contained within the structure and from flow through the front door. Post-flashover, the flaming combustion was sustained by the influx of air through the doorway, and the temperatures throughout the structure remained elevated until suppression.

Figures 6.28 and 6.29 provide a graphic representation of the flow paths within the ranch structure. Figure 6.28 shows the flow of hot gases (red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure open to the kitchen. As the hotter, higher pressure fire gases flowed into other rooms, such as the dining room, breakfast area, and bedroom 2, or out of the front door, the fresh air (green arrows) in those rooms was displaced toward the area of origin. This represents the availability of oxygen needed for flashover. Post-flashover, the measurable air within the structure was minimal and supplied primarily through the front door. The remainder of flow movement within the structure was the circulation of combustion products, as represented by the predominant red arrows in Figure 6.29. Bedrooms 1 and 3 are closed and are not part of the flow paths.

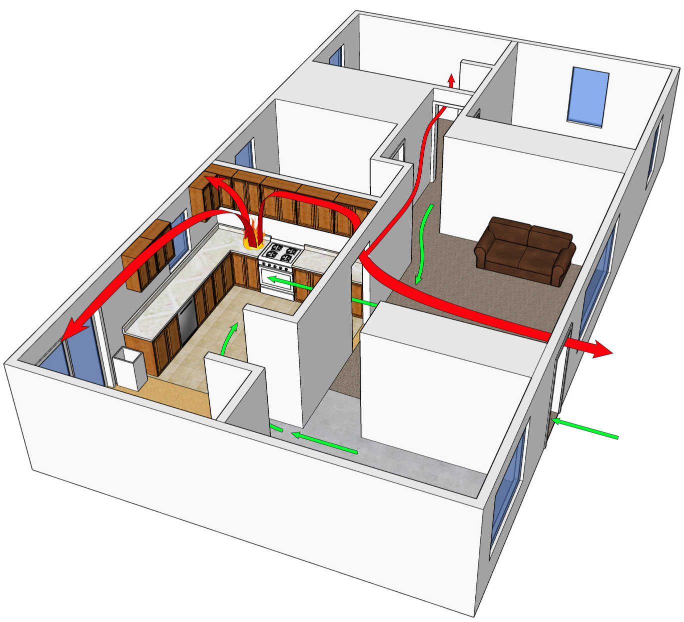


Figure 6.28: Drawing of the pre-flashover flows within the ranch structure, kitchen fire with open front door.

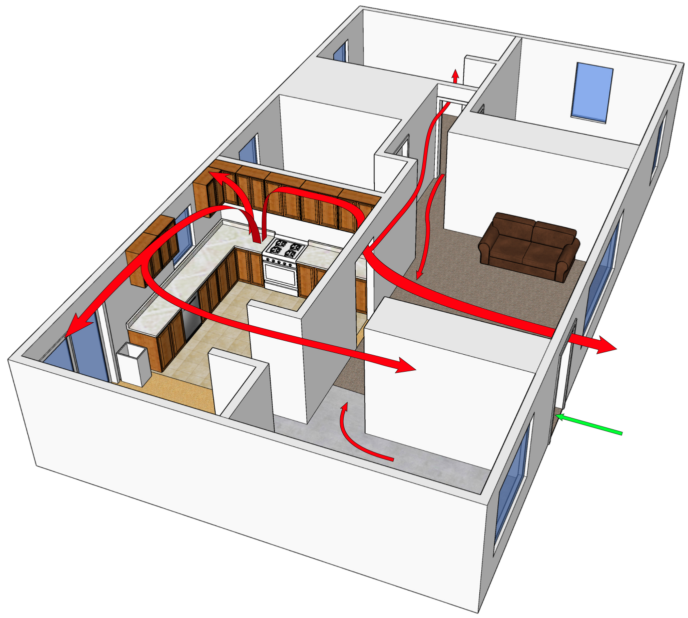
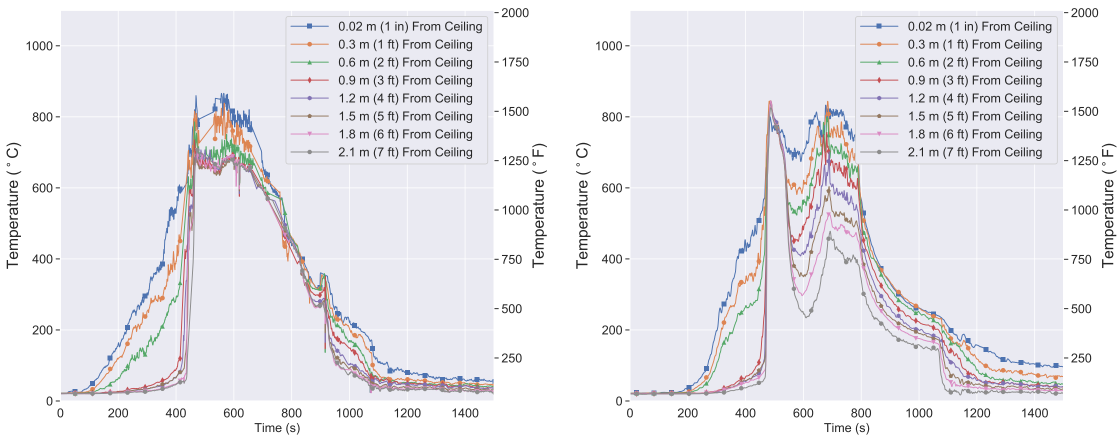


Figure 6.29: Drawing of the post-flashover flows within the ranch structure, kitchen fire with open front door.

For the open door kitchen fires, the thermocouple arrays in the kitchen for Experiment 10 and Experiment 11 showed similar initial growth and transition to flashover times as shown in Figure 6.30. There were some differences post flashover; in Experiment 10 the kitchen temperatures from floor to ceiling remained elevated before decaying as oxygen became depleted while in Experiment 11 temperatures decayed earlier, re-stratified but increased for a second time once oxygen values recovered. One procedural difference between these two experiments is that for Experiment 10, the experiment was allowed to proceed through flashover until suppression. In Experiment 11, the front door was closed approximately 320 s after flashover to examine the impact cutting off the oxygen supply.

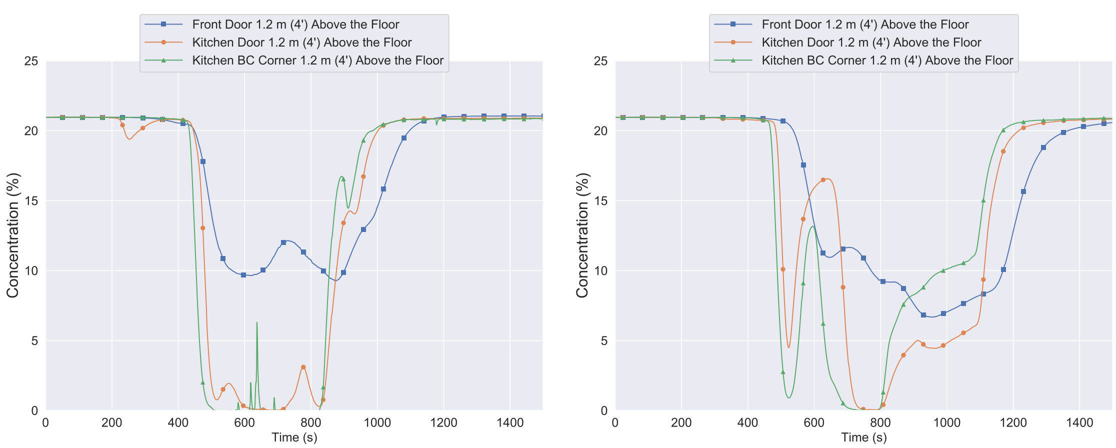


(a) Experiment 10 (b) Experiment 11

Figure 6.30: Comparison of open door kitchen temperatures.

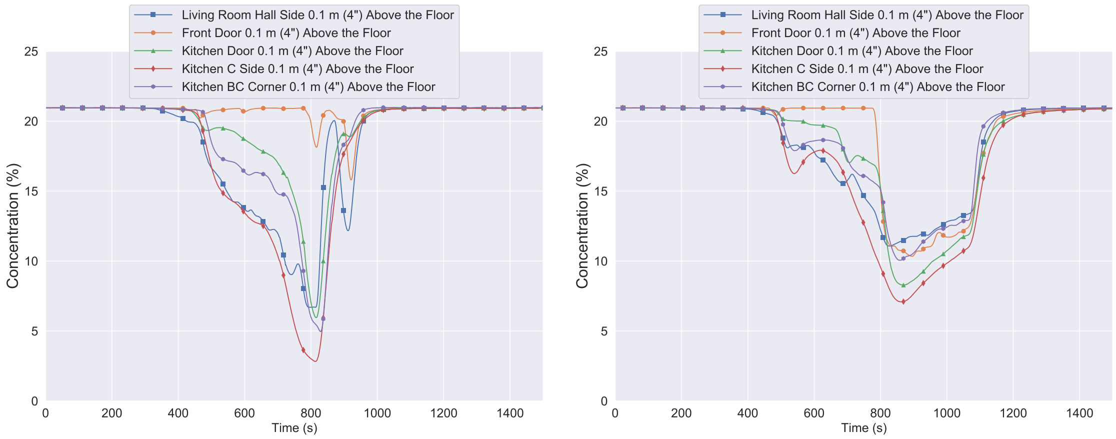
In both experiments post-flashover, the three oxygen levels measured at 1.2 m above the floor in the kitchen and the front door decreased sharply as the kitchen transitioned to flashover, as shown in Figure 6.31. In Experiment 11, however, the oxygen values recovered following the initial drop before dropping to similar levels, as shown in Experiment 10. The cycle of oxygen in Experiment 11 is reflected in the kitchen temperature from Figure 6.30.

The five oxygen levels measured at 0.1 m above the floor decreased to approximately 5% to 10% (as shown for both experiments in Figure 6.32) except for the front door in Experiment 10. In both experiments, the front door oxygen sensor did not decrease with the rest of the measurements because the flow at the front door was bi-directional, meaning the bottom portion of the door was an intake. The difference is that at approximately 800 s after ignition, the front door in Experiment 11 was closed, which caused the front door oxygen to drop.



(a) Experiment 10 (b) Experiment 11

Figure 6.31: Comparison of open door oxygen concentrations at 1.2 m above the floor for kitchen fire.



(a) Experiment 10 (b) Experiment 11

Figure 6.32: Comparison of open door oxygen concentrations at 0.1 m above the floor for kitchen fire.

Fire Damage Comparison

Figures 6.33 and 6.34 show the post fire suppression photographs of the kitchen fire experiments that burned with an open front door. Both fires flashed over the kitchen. Both fires went into decay in 75 s or less post-flashover. For Experiment 10, the heat release from the fire in the kitchen increased to the point that fire spread into the living room and the living room flashed over. Within one minute post-flashover in the living room, the fire extinguishment started. In Experiment 11, the heat release rate rebounded just like in the previous experiment, and the living room carpet near the kitchen door ignited. The temperatures in the living room increased on a similar trend to Experiment 10. The front door was closed to examine the impact on the fire due to stopping the flow of fresh air into the structure.

The walls behind the ignition area have flow patterns from the coffee maker up and around the bottom of the wall cabinet. These patterns are similar to those generated in the kitchen experiments with the closed front door. Hence, these patterns were formed pre-flashover.

In both experiments, the damage to the wall cabinets was similar. Even the remains of the cabinets on the wall were similar. In both fires, the doors of the base cabinets burned through, with the exception of the base cabinet most remote from the fire origin.

The ceiling and floor damage in the area bounded by the kitchen cabinets was consistent with post-flashover damage. In both experiments, the table and chairs in the breakfast area of the kitchen ignited. On the wall behind the table and chairs, soot deposits formed a line of demarcation 0.6 m (2 ft) or less above the floor. Another line of demarcation on the wall formed by thermal damage was located approximately 1.5 m (5 ft above the floor).

(a) Experiment 10 (b) Experiment 11

Figure 6.33: Post-suppression comparison of kitchen room area of origin with a open door.

(a) Experiment 10 (b) Experiment 11

Figure 6.34: Post-suppression comparison of kitchen dining area opposite area of origin with open door.

The next two figures show the post fire conditions in the living room. Figure 6.35 shows the area between the open front door on the left and the open doorway to the kitchen on the right. In other words, this shows the living room portion of the flow path. Figure 6.36 show the sofas located on the wall opposite the wall with the bookcase. In the images from Experiment 10, area between the two doors had fire damage from the ceiling down to the floor, consistent with a post-flashover fire environment. On the other side of the living room, there was fire damage across the ceiling and down the walls to within 0.9 m (3 ft) of the floor. The sofa also ignited.

On the right of the kitchen doorway, there is an interesting damage pattern where the paper on the gypsum board was burned all the way down to the floor and then had a 90 degree intersection with the horizontal line of demarcation on that wall. The vertical portion of that damage was generated by the heat from the burning living room carpet.

The living room images from Experiment 11 show the impact of closing the door prior to the living room transitioning to flashover. The damage was limited to the burned carpet near the kitchen doorway and burned face paper on the ceiling near the doorway. The rest of the damage was limited to soot condensed on the ceiling and walls. Neither the sofa nor the bookcase ignited.

The kitchen fires in both cases transitioned through flashover and then decreased due to a reduction in oxygen. As the fires cycled and the additional oxygen could flow into the kitchen, the heat release of the fires increased, perhaps due to the continued oxygen limit or the reduced amount of fuel in the upper portion of the kitchen, neither kitchen flashed over again. The fire damage patterns in both kitchens are similar, indicating that the flashed over living room or lack thereof had little influence on the fire damage in the kitchen in this set of experiments.

(a) Experiment 10 (b) Experiment 11

Figure 6.35: Post-suppression comparison of living room between kitchen room area of origin and open door.

(a) Experiment 10 (b) Experiment 11

Figure 6.36: Post-suppression comparison of living room wall remote from kitchen with open door.

6.1.3 Bedroom Fires

The bedroom was the room of origin for two experiments with all of the exterior vents closed and two experiments with the front door and bedroom windows open. The fire was ignited in a waste basket next to the mattress in the bedroom using an electric match. The waste basket was adjacent to the mattress (see Figure 3.20), and in all four experiments fire spread to the mattress.

All Exterior Vents Closed

Ranch Experiments 7 and 9 had all of the exterior doors and windows closed. The bedroom fire grew to the point of flashover, but there was insufficient oxygen to support a sustained post-flashover fire. After reaching peak burning, the flaming combustion decreased, and the temperatures throughout the structure began to decrease as a result of reduced levels of oxygen.

Figures 6.37 and 6.38 provide a graphic representation of the flow paths within the ranch structure. Figure 6.37 shows the flow of hot gases (red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure that are open to the bedroom. As the hotter, higher pressure fire gases flowed into other rooms such as the living room or bedroom 2, the fresh air (green arrows) in those rooms was displaced toward the area of origin. This delivered the supply of oxygen needed for combustion. As combustion within the structure ceased due to a lack of oxygen, the measurable flows also stopped, as represented by the smoke-filled areas in Figure 6.38. Bedroom 3 was closed and was not part of the flow path.

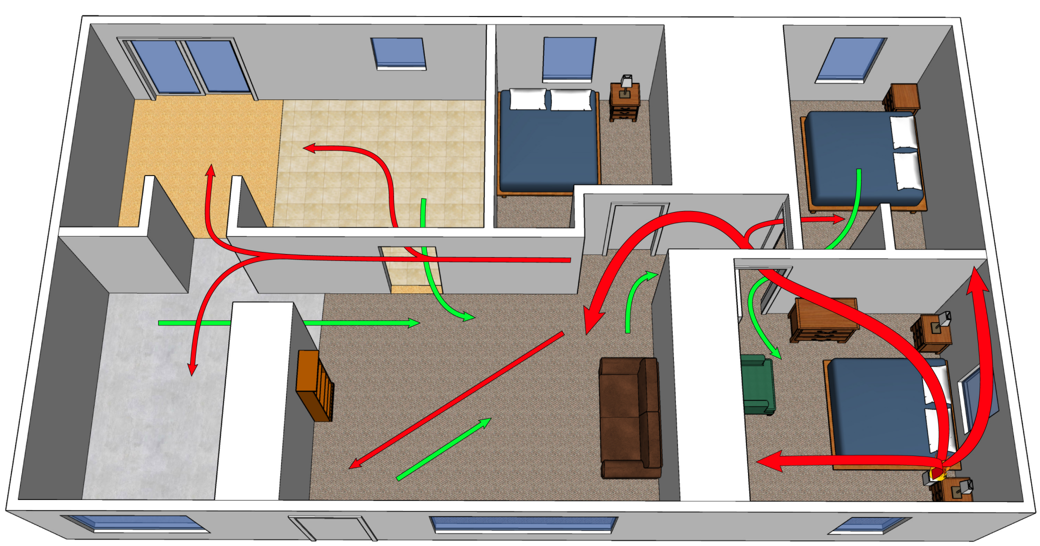
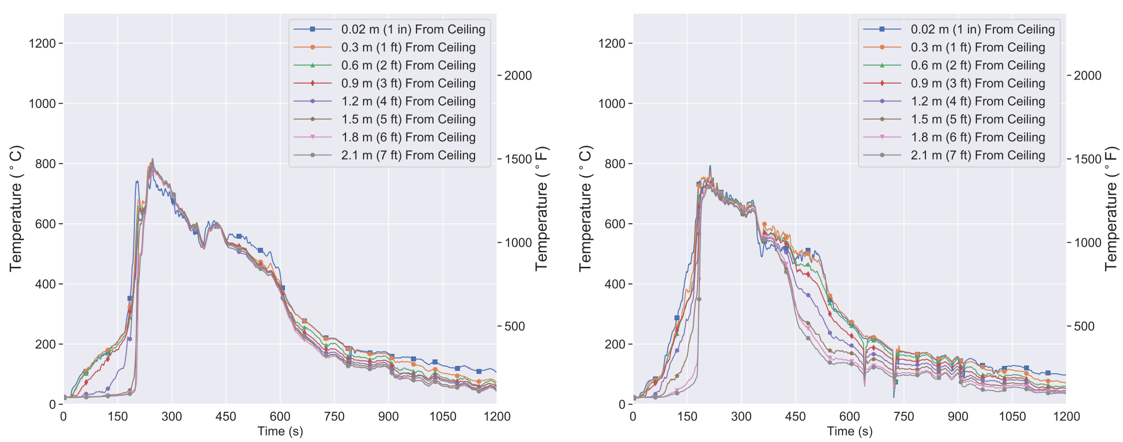


Figure 6.37: Drawing of the pre-flashover flows within the closed ranch structure bedroom fire.

Figure 6.38: Drawing of the post-flashover condition within the closed ranch structure bedroom fire.

The temperature time histories of the bedroom room fires were similar in magnitude, as shown in Figure 6.39. The time to flashover, peak temperature, and decay were all similar.



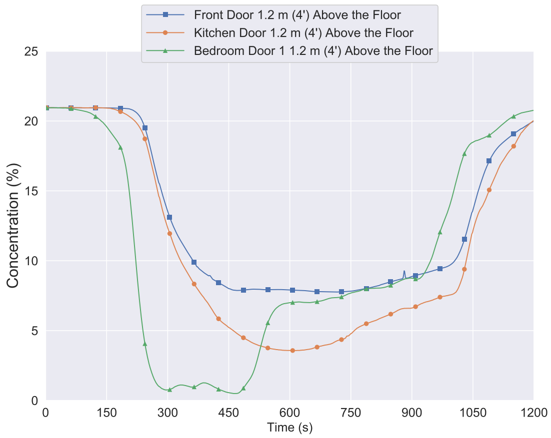
(a) Experiment 7

(b) Experiment 9

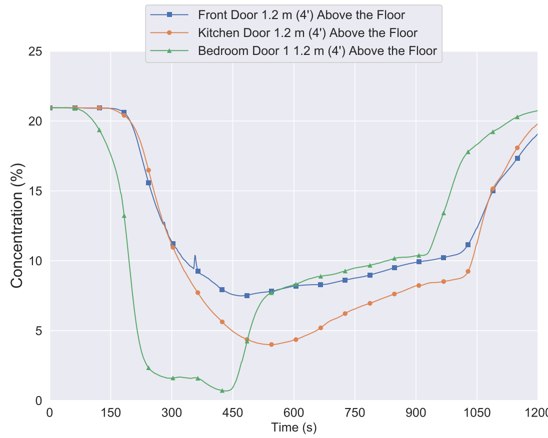
Figure 6.39: Comparison of closed door bedroom fire temperatures.

In both experiments post-flashover, the oxygen concentrations measured at 1.2 m above the floor at the bedroom doorway dropped to less than 1%, the kitchen doorway dropped to 4%, and the front door dropped to 7%, as shown in Figure 6.40. The oxygen concentrations measured at 0.1 m above the floor at the same locations had similar responses but had minimum values between 10%–15%. For the two additional sensors in the bedroom at the 0.1 m elevation, the oxygen dropped below

5% in both experiments. Figure 6.41 shows the oxygen concentrations at 0.1 m. While each of the oxygen concentration values between are not exact matches, the trends are similar, and the relationship between oxygen values and the increase and decrease in temperatures in the living room were consistent.

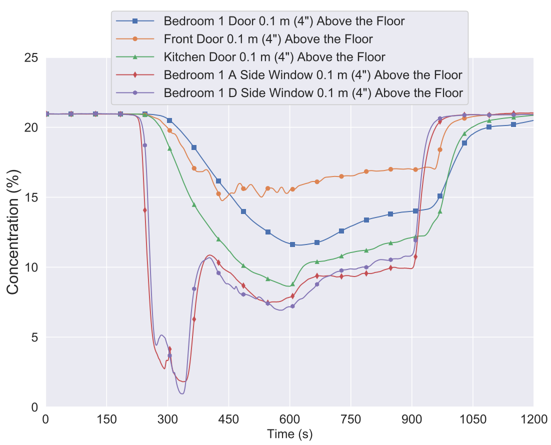


(a) Experiment 7

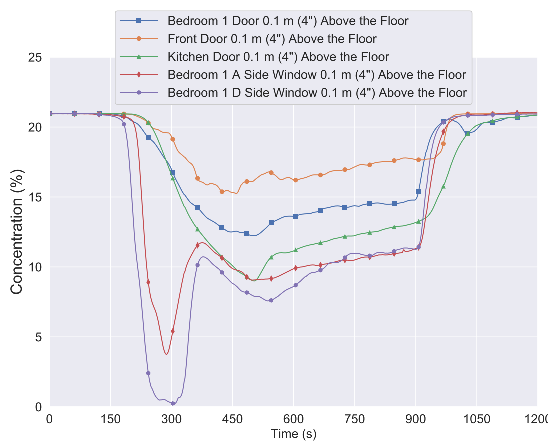


(b) Experiment 9

Figure 6.40: Comparison of closed door oxygen concentrations at 1.2 m above the floor for bedroom fire.



(a) Experiment 7



(b) Experiment 9

Figure 6.41: Comparison of closed door oxygen concentrations at 0.1 m above the floor for bedroom fire.

Fire Pattern Comparison

Figures 6.42 through 6.45 show post fire suppression images from experiments 7 and 9, the bedroom fire with no exterior vents scenario. Both fires flashed over and then decayed to the point of flame extinguishment as a result of oxygen depletion. At 15 min after ignition, firefighters vented the bedroom and no flames were visible. No rekindle occurred after ventilation.

The first pair of images, Figures 6.42 and 6.43, show the areas of origin with the furnishings still in place. The bed, nightstands, dresser, and chair had damage consistent with being ignited and burned over their exposed surfaces. Heat damage to the upholstered chair was similar in both experiments and seemed to start from the top down.

(a) Experiment 7 (b) Experiment 9

Figure 6.42: Post-suppression comparison of bedroom 1 area of origin with a closed door.

(a) Experiment 7 (b) Experiment 9

Figure 6.43: Post-furniture removal comparison of bedroom 1 area of origin with closed door and windows.

The next sets of images have the furniture removed. Looking at the area of origin photographs, both ceilings had the paper burned off of the gypsum board from the area over the bed to the front wall, and the wall with the chair against it. The walls have similar damage in both experiments, in part because of the soot patterns formed in the shielded areas behind the furniture and the large window openings in two of the walls. In both experiments, the front wall received thermal damage across the upper half of the wall that was across from the bedroom door. The lack of damage on the lower portion of the wall may be a result of the chair obstructing the air flow into the bedroom. Approximately 0.3 m to the side of the front window, the thermal damage demarcation line moved toward the floor. The thermal damage continued across the front walls above and below the window. Continuing across the front wall to the corner near the point of ignition, the thermal damage extended over the height of the wall. The doorway walls opposite the front walls had limited thermal damage with discrete areas in the upper half of the walls where the paper was burned off of the gypsum wallboard. The wall adjacent to the doorway in both experiments had a protected area pattern behind the upholstered chair. The walls had a light coating of soot and some discrete thermal damage areas in the upper left half of the wall. On the downstream side of the chair there was a clear area on the wall. Also in both fires, portions of the bedroom door from the door knob up were burned away.

Most of the fire damage to the carpet and sub-floor occurred along the air intake path from the bedroom door, starting just past the chair, past the foot of the bed, and around the side of the bed between the bed and the front wall. This was due not only to the air flow there, but also because the carpet was pre-heated and pyrolyzed due to radiation from the fire burning from the night stand and side of the bed.

(a) Experiment 7 (b) Experiment 9

Figure 6.44: Post-suppression comparison of bedroom 1 opposite the area of origin with closed door.

(a) Experiment 7 (b) Experiment 9

Figure 6.45: Post-furniture comparison of bedroom 1 wall opposite area of origin with closed door and windows.

Front Door and Bedroom Windows Open

Ranch Experiments 12 and 13 had all of the exterior doors and windows closed except for the open front door and bedroom 1 windows. The bedroom fire grew to the point of flashover within the bedroom, and post-flashover fire conditions were maintained due to the open windows and door until suppression. The flashover and subsequent fully-developed state was supported by oxygen contained within the structure and from flow through the front door and open windows.

Figures 6.46 and 6.47 provide a graphic representation of the flow paths within the ranch structure. Figure 6.46 shows the flow of hot gases (red arrows) beginning at the area of fire origin and flowing throughout the adjoining rooms in the structure that are open to bedroom 1. As the hotter, higher pressure fire gases flowed into other rooms, such as bedroom 3, the living room, out of the front door, or out of the bedroom windows, the fresh air (green arrows) in those rooms was displaced toward the area of fire origin. This represents the availability of oxygen needed for flashover. Post-flashover, the measurable air within the structure was minimal and supplied primarily through the open windows and front door. The remainder of flow movement within the structure was the circulation of combustion products, as represented by the predominant red arrows in Figure 6.47. Bedrooms 3 was closed and was not part of the flow path.

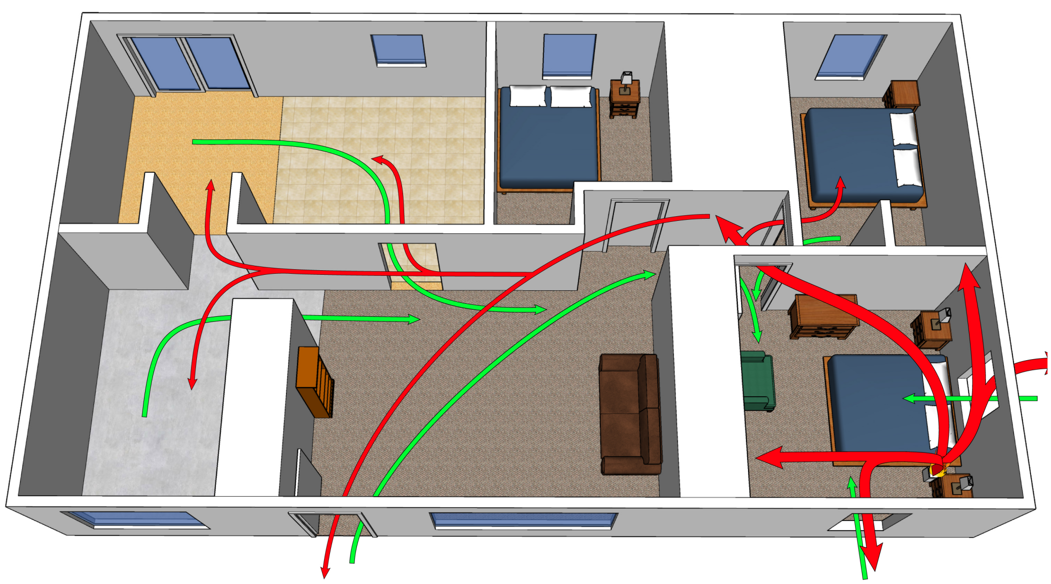


Figure 6.46: Drawing of the pre-flashover flows within the ranch structure bedroom fire with open front door and bedroom windows.

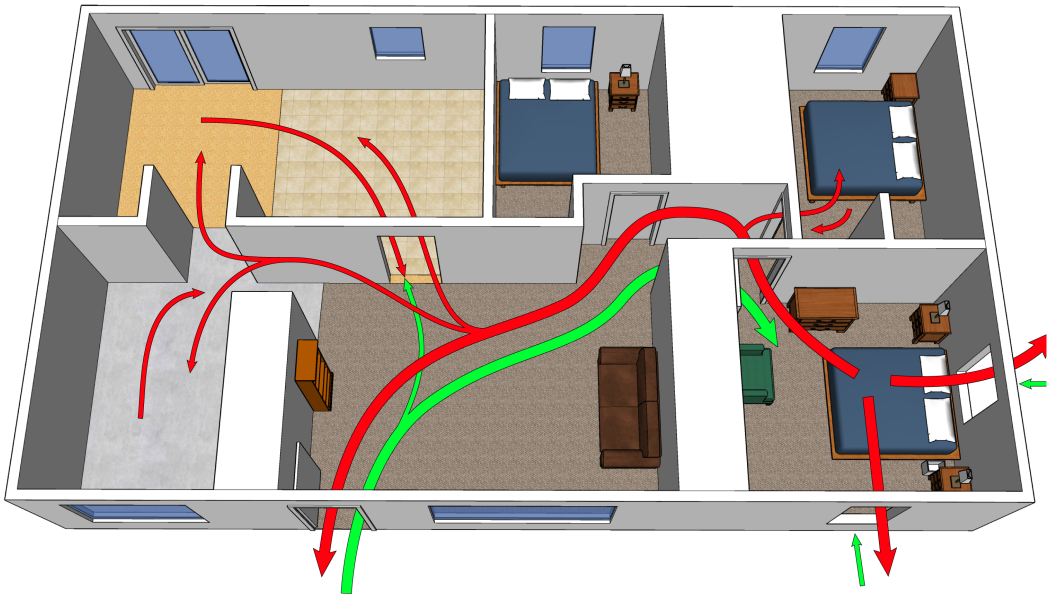
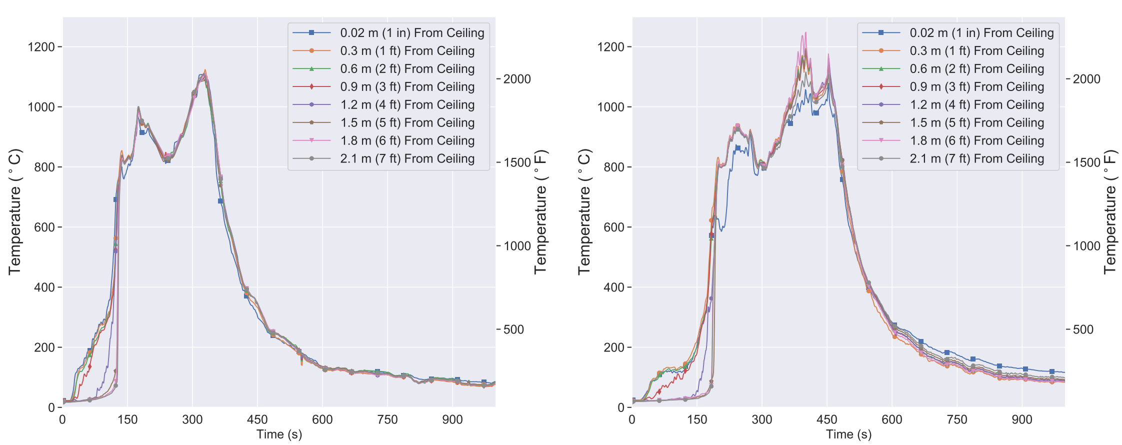


Figure 6.47: Drawing of the post-flashover flows within the ranch structure bedroom fire with open front door and bedroom windows.

The temperature time histories of the bedroom room fires were similar in magnitude as shown in Figure 6.48. The time to flashover, peak temperature, and decay were all similar. In both experiments, the rooms transitioned to flashover with temperatures peaking near 1000 °C (1832 °F), going through a slight decay before hitting a second peak prior to suppression.

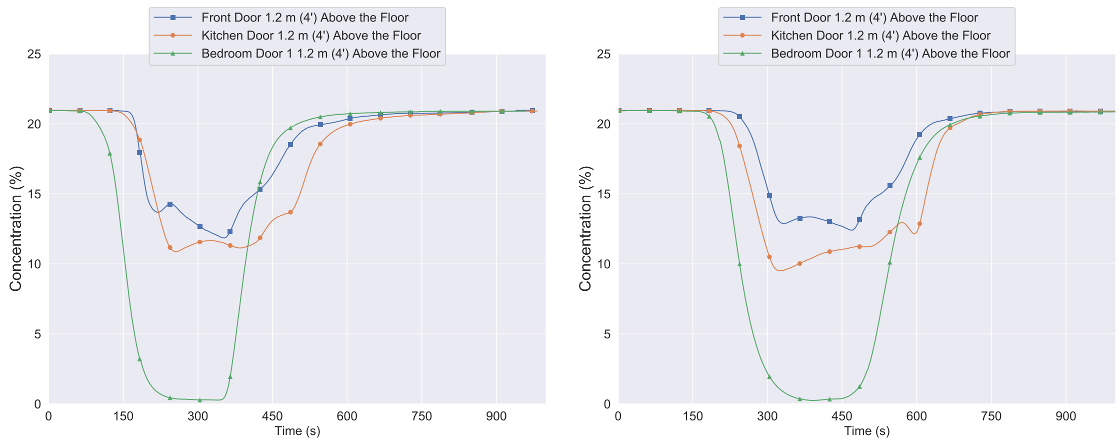


(a) Experiment 12

(b) Experiment 13

Figure 6.48: Comparison of open door and window bedroom fire temperatures.

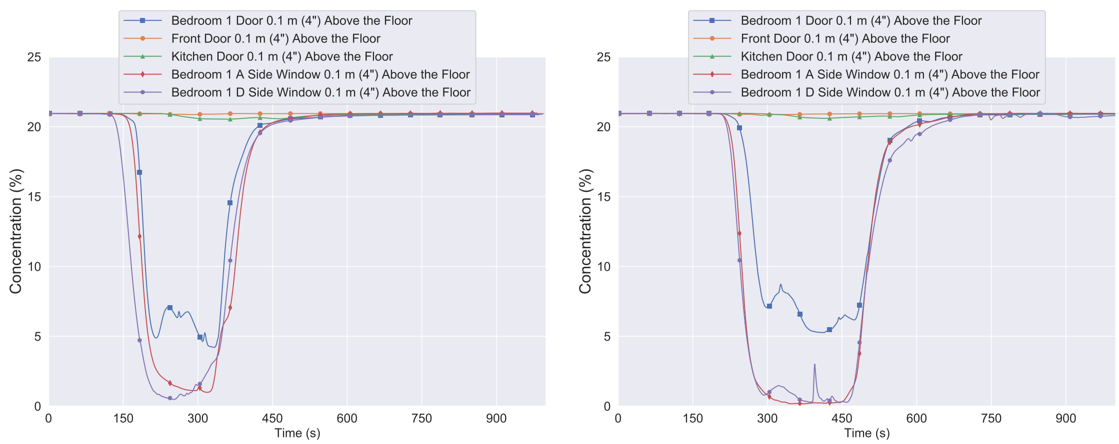
In both experiments, the oxygen levels measured at the bedroom doorway at 1.2 m above the floor dropped to near 0%, while the front door and kitchen doorway (both further from the fire room) had oxygen concentrations between 10% and 15% as shown in Figure 6.49. All five oxygen sensors at the 0.1 m elevation had similar responses: The sensors closest to the front door had the highest oxygen concentrations, while the two sensors in the bedroom below the open windows had the lowest values, as Figure 6.50 shows.



(a) Experiment 12

(b) Experiment 13

Figure 6.49: Comparison of open door and windows oxygen concentrations at 1.2 m above the floor for bedroom fire.



(a) Experiment 12

(b) Experiment 13

Figure 6.50: Comparison of open door and windows oxygen concentrations at 0.1 m above the floor for bedroom fire.

Fire Damage Comparison

These bedrooms had three open exterior vents, the front door and both windows in the bedroom. This additional exhaust and airflow allowed these fires to transition through flashover and then continue to burn with temperatures in excess of 800 °C (1472 °F) for at least 200 s before suppression. Figures 6.51 through 6.56 have post fire suppression images from experiments 12 and 13.

The first pair of images (see Figures 6.51 and 6.44) show the areas of origin with the furnishings still in place. In both experiments, the bed padding and fabric had burned away so that the bed springs were visible. The nightstands and dresser were charred on exposed surfaces. The upholstery on the chairs had been burned away, leaving only the charred wood frame.

(a) Experiment 12 (b) Experiment 13

Figure 6.51: Post-suppression comparison of bedroom 1 area of origin with an open front door and bedroom windows.

(a) Experiment 12 (b) Experiment 13

Figure 6.52: Post-suppression comparison of bedroom 1 opposite the area of origin with an open front door and bedroom windows.

Figures 6.53 and 6.54 contain photographs taken after the furniture was removed. Looking at the area of origin photographs, both ceilings were clean burned over the majority of their area. Examining the wall behind the bed, on the ignition side the wall had more thermal damage, and portions of that section of wall were clean burned. On the left side there was thermal damage from near the floor up to the ceiling, but only small sections of the wall were clean burned. The bed burned away to the point where it no longer provided a protected area. The only protected patterns on these walls were behind the nightstands. The wall damage was similar in both experiments.

In both fires, the upper half of the left wall had most of the paper burned off between the doorway and the corner by the nightstand. The lower half of the wall received less damage than the upper half. A condensed soot pattern was formed behind the dresser. A faint convection pattern on the wall moved across the dresser from the doorway toward the window.

The bedroom doors were burned away completely in both experiments. The carpet, padding, and sub-floor were burned over the majority of the floor area in both experiments. Most of the fire damage to the carpet, padding, and sub-floor occurred along the air intake path from the bedroom door under the bed and around the side of the bed between the bed and the front wall. To the left of the head of the bed, under the nightstand and dresser, and between the two furniture items, the sub-floor was protected in both experiments. In terms of repeatability, the fire damage in both bedrooms was similar.

(a) Experiment 12

(b) Experiment 13

Figure 6.53: Post-furniture removal comparison of bedroom 1 area of origin with an open front door and bedroom windows.

(a) Experiment 12

(b) Experiment 13

Figure 6.54: Post-furniture comparison of bedroom 1 wall with doorway to hall, open front door and bedroom windows.

The last set of photographs for these two experiments show the conditions in the living room, which served as one of the flow paths for gases to exit the structure and fresh air to enter the structure. Figure 6.55 shows the living room from the front door, looking toward the hall leading to the fire room. In both experiments, flames exited the bedroom and flowed into the hall. The carpeting in the hall burned and spread to the living room to the point of igniting the left side of the sofa. The arched line of demarcation over the sofa was similar in both experiments. The soot patterns and their lines of demarcation on the walls in the living room were similar in height above the floor, and by observation, in amount. In Experiment 12, more than half of the ceiling had thermal damage. In Experiment 13, less than half of the ceiling had thermal damage. Figure 6.56 shows the portion of the living room toward the open front door. It shows that the damage was reduced as the distance increased from the fire room. The bookcases did not ignite in either experiment.

No clear fire pattern identifying an area of origin appeared on the walls. There are several reasons for this: The ventilation points near the point of ignition, the increased post-flashover heat release rate in the room, and the ignition fire, which did not contact the wall early in the early stage of the fire.

(a) Experiment 12 (b) Experiment 13

Figure 6.55: Post-furniture comparison of living room area adjacent to bedroom hall, open front door and bedroom windows.

(a) Experiment 12 (b) Experiment 13

Figure 6.56: Post-furniture comparison of living room area adjacent to front door, open front door and bedroom windows.

6.2 Impact of Ventilation

6.2.1 Single Story Structure

In the previous section, the repeatability of pairs of fire experiments with the same ventilation configuration were compared. In this section, the single story experiments with different ventilation configurations are compared.

Living Room Fires

The fires that were ignited on a sofa in the living room were conducted with three different ventilation conditions: all exterior vents closed, front door open, and front door and remote vent open.

The comparison between the no exterior ventilation and the open front door experiments are first. In the experiments in the closed structures, the living room fires were ignited, flashed over, and self extinguished in less than 5 min. The post flashover burn time was 30 s or less, due to oxygen depletion. In the living room fires with the front door open, the supply of oxygen-laden fresh air allowed the fires to continue to burn they became fuel depleted. These fires were extinguished by a hose stream prior to running out of fuel. The time from ignition to the start of suppression was approximately 10 min. Both experiments burned for approximately 7 min post-flashover.

Figures 6.57 and 6.58 show the post fire suppression photographs of the living rooms that burned with no open exterior vent and with the front door open, respectively. The difference in the extent of the fire damage is clear. The open door provided an exhaust vent for oxygen-depleted combustion products and an intake vent for air. The continued supply of air supported combustion for a longer period of time. During that time, the combustion zone moved from the area of origin toward the open front door, and then later in the experiment the fire began to move back toward the area of origin.

(a) Experiment 1 (b) Experiment 2

Figure 6.57: Post-suppression comparison of living room area of origin, with closed door.

(a) Experiment 3 (b) Experiment 4

Figure 6.58: Post-suppression comparison of living room area of origin, with open door.

In the open door experiments, when the combustion moved toward the front door, the TV stand was ignited. The difference in the fire patterns created on the wall near the front door depending on whether the door was opened or closed appears in Figures 6.59 and 6.60. The ventilation-impacted fire damage patterns generated by the burning dresser next to door with an air velocity of 1.4 m/s (3 mph) entering the lower portion of the open doorway appear in Figure 6.60.

(a) Experiment 1 (b) Experiment 2

Figure 6.59: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with closed door.

(a) Experiment 3 (b) Experiment 4

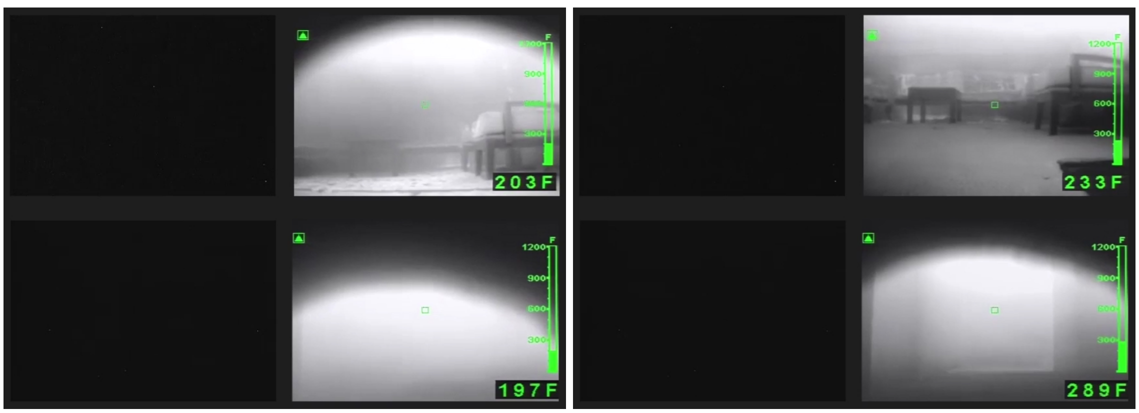
Figure 6.60: Post-overhaul comparison of living room wall opposite the area of origin and adjacent to front door with open door.

For flaming fire to exist, it needs fuel, heat, and oxygen to support the sustained chemical reaction. The mixture of fuel and oxygen needs to be in an appropriate proportion in order to burn. Too much fuel, and the mixture is too rich to ignite. Too much oxygen, and the mixture may be too lean to ignite. The ideal mixture of air to fuel is referred to as a stoichiometric mixture. This means that the air has enough oxygen to burn all of the fuel with no air left over. As an example, the stoichiometric air - fuel ratio for gasoline is 14.7 to 1. The review of the experiments in this study so far indicates that residential compartment fires generate a fuel-rich environment.

The next set of figures have images from video cameras and thermal imaging cameras that were installed in the structures side by side. The thermal imager provided a sense of where the heat was in the structure at a given time even if the video camera view was obscured by smoke. This also gave a sense of where the air-fuel mixture was in range for combustion and generating heat

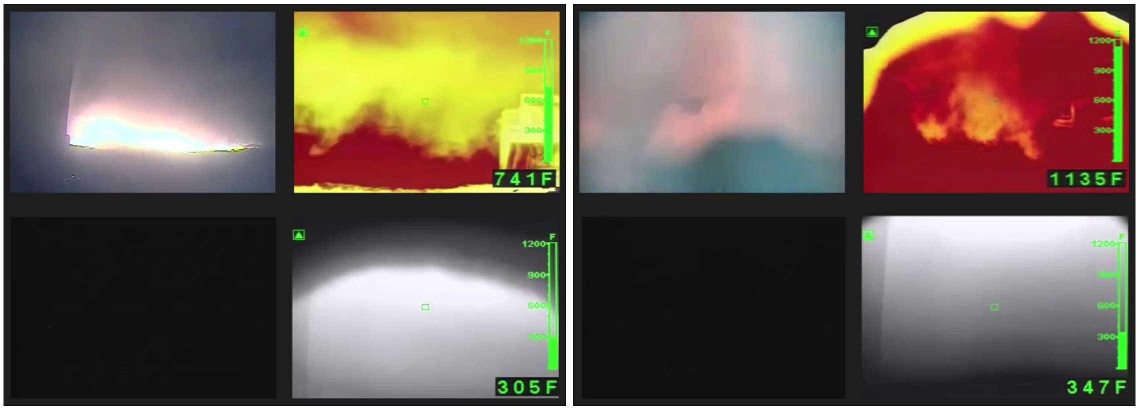
Pairs of video and infrared images are from two different positions. The two upper views in each set of images are from cameras installed between the front door and the TV stand and aimed toward the area of origin. The lower two views in each set of images are from cameras installed in the dining room and aimed toward the living room. The center of the thermal image view was approximately 1 m (3 ft) to the left of the point of fire origin.

All of the images were taken at 300 s after ignition. The images in Figure 6.61 show that in Experiments 1 and 2 (exterior vents closed), the fire had depleted the oxygen levels within the structure such that the flames self-extinguished shortly after flashover. The Figure 6.62 images were from Experiments 3 and 4, which had the front door open. The air flow through the open door enabled the fire to continue to burn post-flashover. However, at this point, the fire was only burning near the open front door where the hot fuel gases could mix with oxygen entering the door (see upper images). At the same time, the gas-phase combustion near the area of origin had stopped due to a lack of oxygen (see lower images). In both open door experiments, shortly after flashover the estimated wall temperature adjacent to the point of ignition decreased to less than 200 °C (400 °F).



(a) Experiment 1 (b) Experiment 2

Figure 6.61: Pairs of video and infrared images from two views of the living room for Experiments 1 and 2 at 300 s after ignition, closed door. The two upper views in each set of images are from cameras near the front door and looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, with the center of the image view approximately 1 m to the left of the area of origin.



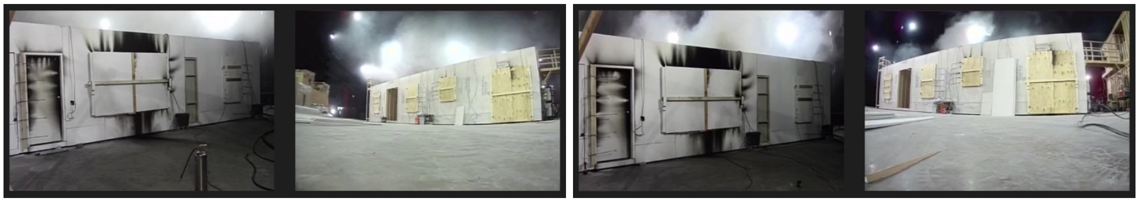
(a) Experiment 3 (b) Experiment 4

Figure 6.62: Pairs of video and infrared images from two views of the living room for Experiments 3 and 4 at 300 s after ignition, open door. The two upper views in each set of images are from cameras near the front door and looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, with the center of the image view approximately 1 m to the left of the area of origin.

Another way to examine the impact ventilation had on the fire is to look at images of the exterior of the structures. Again, these images were captured at 300 s after ignition for direct comparison with the thermal images above.

Figure 6.63 shows the lack of smoke flow out of the structure at this time. The soot marks on the front door and above and below the front window shutters are evidence that as the fire was growing, the gas pressure inside the structure was sufficient to force smoke around the edges of the closed vents. In the case of the front door, there was evidence that the smoke was all the way down to the floor when it was being forced out close to the bottom of the door. By 300 s after ignition the fires self extinguished due to a lack of oxygen. The gas temperatures have decreased and the pressure inside the structure was less then the pressure outside of the structure, so the smoke stopped pushing out.

Experiments 3 and 4 had the front door open from the time of ignition. Images of the front and rear of the exterior of the structure with the open door appear in Figure 6.64. In both experiments, the fire can be seen burning in close proximity to the open door. The open door is acting as a bidirectional vent with both an air intake and an exhaust.



(a) Experiment 1 (b) Experiment 2

Figure 6.63: Images of the exterior of the structure for Experiments 1 and 2 at 300 s after ignition, closed door. The left view of each pair of images showss the front side. The right view of each image pair showss of the back side.

(a) Experiment 3 (b) Experiment 4

Figure 6.64: Images of the exterior of the structure for Experiments 1 and 2 at 300 s after ignition, open door. The left view of each pair of images shows the front side. The right view of each image pair shows of the back side.

In Experiment 5, the ventilation of the structure was increased with the addition of the bedroom 3 window open for the duration of the experiment. Recall from Figure 4.25, temperatures within the living room remained elevated compared to Experiments 3/4. The increased temperatures were the result of more energy being released from the fire. As a result, the living room sustained more damage. Of particular interest in Figure 6.65, which compares Experiments 4 and 5, is the additional damage on the left side of the back wall of the living room toward the hallway. The open bedroom 3 window provided a second exhaust path for the hot combustion products to travel.

(a) Experiment 4 (b) Experiment 5

Figure 6.65: Post-suppression comparison of living room area of origin, with open door and open window (Experiment 5 only).

To further compare the impact of ventilation, consider the post suppression fuels in both bedroom 2 and bedroom 3. Figure 6.66 shows the differences that resulted from having a closed window (bedroom 2) and an open window (bedroom 3). In bedroom 2, there is evidence of smoke damage due to soot deposition but no indication of flame combustion. In bedroom 3, there is noticeable damage to the exterior wall and evidence of burning on the foam mattress topper of the bed. The open window allowed the high temperature unburned fuel from the living room to mix with the air entrained from the open window and ignite.

(a) Experiment 5, Bedroom 2 (b) Experiment 5, Bedroom 3

Figure 6.66: Post-suppression comparison of bedroom 2 (closed window) and bedroom 3 (open window) from Experiment 5.

Kitchen Fires

The kitchen fires were conducted with two different ventilation conditions: all exterior vents closed, and the front door open. The two kitchen fires conducted with no exterior ventilation grew from a small flame to flames involving cabinets and impacting the ceiling, and then in both cases the fires self-extinguished. This fire behavior resulted in a limited amount of fire damage in each kitchen. Each kitchen had a similar fire pattern that could be traced back to the area of origin.

The two kitchen fires ignited with the front door open resulted in flashover with sustained post-flashover burning until firefighter intervention. The additional ventilation resulted in more fire damage in each kitchen that involved all of the cabinets, charred the table and chairs in the eat-in kitchen area, and inflicted thermal damage to large sections of the ceiling, walls, and floor.

Figures 6.67 and 6.68 show the post fire suppression photographs of the both the kitchens burned with no open exterior vent and with an front door open, respectively. The difference in the extent of the fire damage is visible. The open door provided an exhaust vent for oxygen-depleted combustion products and an intake vent for air. The continued supply of air supported combustion for a longer period of time. In Experiment 10, the combustion zone moved from the kitchen toward the open front door and then flashed over the living room.

(a) Experiment 6 (b) Experiment 8

Figure 6.67: Post-suppression comparison of kitchen room area of origin with a closed door.

(a) Experiment 10 (b) Experiment 11

Figure 6.68: Post-suppression comparison of kitchen room area of origin with am open door.

The next set of figures are images from video cameras and thermal imaging cameras installed in the structures side by side. As before, the thermal imager will give us an idea of where the heat was in the structure at a given time even if the video camera view was obscured by smoke. This also gave a sense of where the air-fuel mixture was in range for combustion and generating heat.

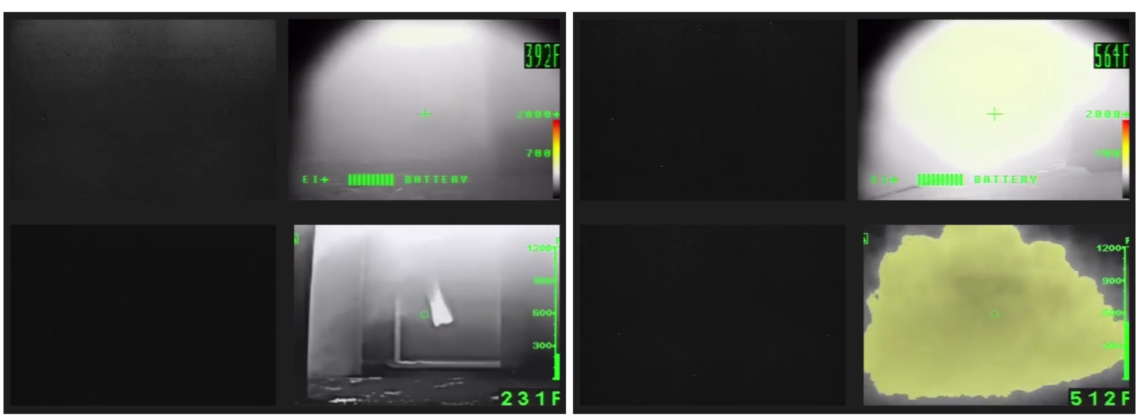
The pairs of video and infrared images are from two different positions. The two upper views in each set of images are from cameras installed next to the table and chairs in the kitchen and aimed toward the area of origin. The lower two views in each set of images are from cameras installed in the dining room and aimed toward the living room. This provides view of the hot gas flows out the kitchen doorway and the conditions in the living room.

The images in Figure 6.69 show that in Experiments 6 and 8 (exterior vents closed), the fire had depleted the oxygen levels within the structure such that the flames self-extinguished shortly after flashover. These images were taken at 600 s after ignition.

(a) Experiment 6 (b) Experiment 8

Figure 6.69: Pairs of video and infrared images for the kitchen Experiments 6 and 8 at 600 s after ignition, closed door. The two upper views in each set of images are from cameras looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room looking past the kitchen doorway and into the living room.

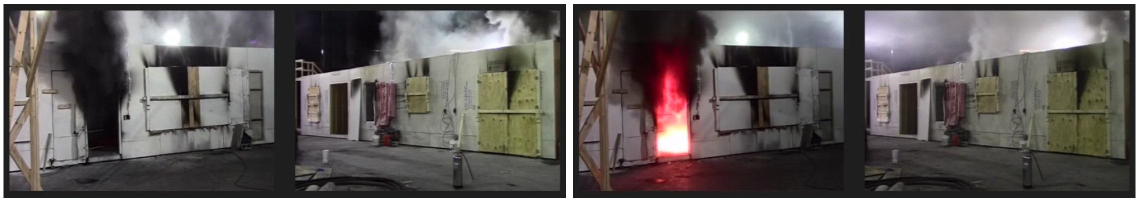
The images in Figure 6.70 were taken from Experiment 10, which had the front door open. The air flow through the open door enabled the fire to continue to burn post-flashover. The kitchen fire started to flashover at 405 s after ignition. However by 480 s, the structure was filled with smoke, the kitchen filled with smoke, and the fire size appeared to decrease (see Figure 6.70a). Five minutes later, burning continued in the kitchen, but the fire had now spread and flashed over the living room (see lower images).



(a) Experiment 10, 480 s (b) Experiment 10, 780 s

Figure 6.70: Pairs of video and infrared images for the kitchen Experiments 10 and 11 at 480 s after ignition, closed door. The two upper views in each set of images are from cameras looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room looking past the kitchen doorway and into the living room.

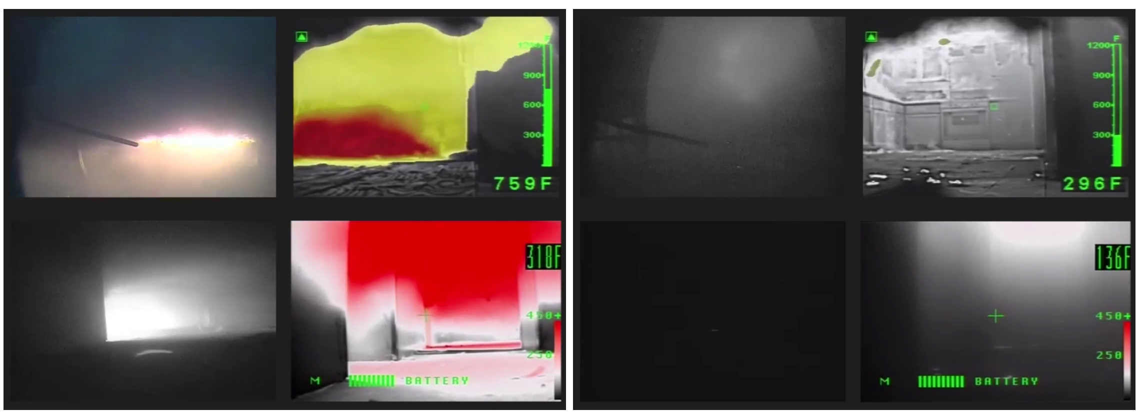
Figure 6.71 shows exterior views of the front and rear of the structure at two different times. Figure 6.71a shows black smoke flowing out of the upper half of the open front doorway during the kitchen post-flashover. Figure 6.71b shows the exterior conditions during the flashover in the living room.



(a) Experiment 10, 480 s after ignition (b) Experiment 10, 780 s after ignition

Figure 6.71: Images of the exterior of the structure for kitchen Experiment 10, closed door. The left view shows the front side. The right view shows the back side.

Kitchen Experiment 11 was also conducted with an open front door. Figure 6.72 shows two sets of images. The fire in the kitchen had auto-ignited the kitchen floor at 460 s after ignition. The images in Figure 6.72a were captured at 480 s after ignition. Within 10 s after this image was recorded, the fire in the kitchen began to decrease. The second set of images was taken 2 minutes after the first set, at 600 s after ignition. The temperatures within the structure were decreasing even though the front door was open and fuel was available.



(a) Experiment 11, 480 s after ignition (b) Experiment 11, 600 s after ignition

Figure 6.72: Pairs of video and infrared images from two views of the kitchen Experiment 11 at 480 s and 600 s after ignition, respectively, open door. The two upper views in each set of images are from cameras looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, looking past the kitchen doorway and into the living room.

Figure 6.73 shows the front and rear exterior views of the structure at 480 s and 600 s after ignition. Looking at the latter of the two images of the front door, (Figure 6.73b), the fire can be seen in the living room, burning low to the floor.

Experiment 10 demonstrated that the kitchen fire would grow to flashover, go into a period of decay, and move into the living room toward the fresh air vent, and flashover of the living room. During Experiment 11, the fire growth was observed to be following the path of Experiment 10, so

(a) Experiment 11, 480 s after ignition (b) Experiment 11, 600 seconds after ignition

Figure 6.73: Images of the exterior of the structure for kitchen Experiment 11, open door. The left view shows the front side. The right view shows the back side.

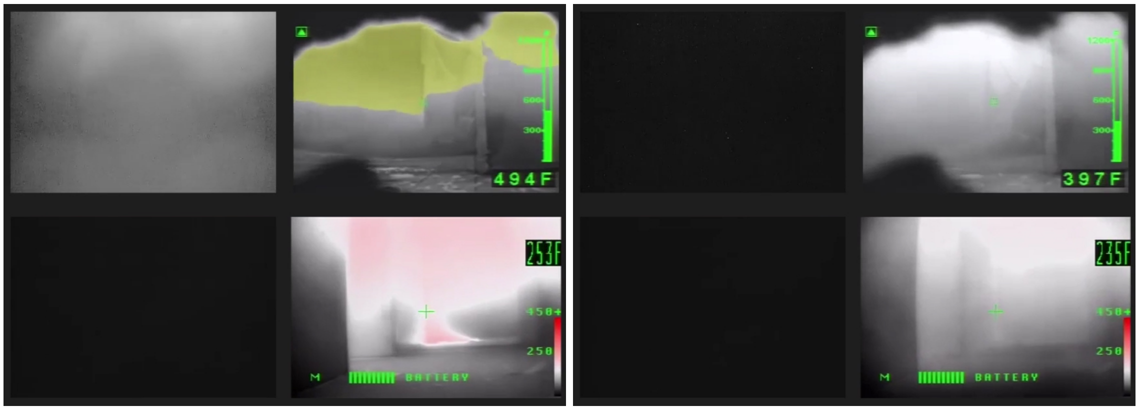
a decision was made to close the front door as the fire was growing in the living room to examine the impact of stopping the supply of air to the fire. The door was closed at 785 s after ignition.

Figure 6.74 shows the differences in the flow path area of the living room between the open front door and the doorway to the kitchen for Experiments 10 and 11. Closing the door prevented the flashover in the living room in Experiment 11.

(a) Experiment 10 (b) Experiment 11

Figure 6.74: Post-suppression comparison of living room between kitchen room area of origin and open door.

The infrared images provide an idea of how quickly conditions changed when air flow into the structure stopped. Figure 6.75 has two sets of images; the upper pair were recorded at 777 s after ignition, just seconds before the door closed. At this time, the temperatures in the kitchen were higher than those in the living room, but flames were visible burning the living room carpet. Temperatures near the living room ceiling were close to 600 °C (1112 °F) and rising just before the door was closed. The lower pair of video and thermal images was taken at 800 s after ignition, 15 s after the door was closed. In the first 15 s after the door closure, the gas temperatures near the ceiling of the living room decreased by almost 200 °C (400 °F). During that same period, the oxygen concentration measurement sampled 100 mm (4 in.) above the floor next to the front door dropped from more than 20% to below 15%. Closing the door essentially shut the fire off due to a lack of oxygen.



(a) Experiment 11, 777 s after ignition

(b) Experiment 11, 800 s after ignition

Figure 6.75: Pairs of video and infrared images from two views of the kitchen Experiment 11 at 480 s and 600 s after ignition, respectively, open door. The two upper views in each set of images are from cameras looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, looking past the kitchen doorway and into the living room.

Bedroom Fires

The bedroom fires were ignited in a plastic waste container that had newspaper in it. The waste container was positioned between the bed and the side of the nightstand so that about a third of the waste container was between the two pieces of furniture. The waste container was not up against the wall. The bedroom fires had two different ventilation conditions: all exterior vents closed, and front door and bedroom windows open.

The fire damage comparison between the no exterior ventilation and the open front door experiments are made first. For the experiments in the closed structures, the living room fires were ignited, flashed over, and self-extinguished in less than 5 min. The post-flashover burn time was 30 s or less due to oxygen depletion.

In the fires with the front door and the windows open, the supply of air allowed the fires to continue to burn post-flashover until the fires were suppressed. These fires were extinguished by a hose stream prior to running out of fuel. The time from ignition to the start of suppression was 330 s in Experiment 12 and 450 s in Experiment 13. The fire in Experiment 12 burned for approximately 200 s post-flashover, while the fire in Experiment 13 burned for approximately 240 s post-flashover.

Figure 6.76 shows the post fire suppression photographs of the bedroom from Experiments 7 and 9 that burned with no open exterior vent. Similar photographs appear in Figure 6.77 for Experiments 12 and 13, which were conducted with the front door and bedroom windows open. The bedroom fires with the open door and windows were able to burn for a longer time post-flashover. As a result, room of origin in Experiment 12 and 13 had more fire damage. In the experiments with the open vents, the fire also spread into the hallway, burned the door of the adjacent bedroom, and ignited the sofa in the living room. It is important to note that raising the height of the window sill above the neutral plane could change the amount of fire damage adjacent to the windows, as it would reduce the air flow into the room.

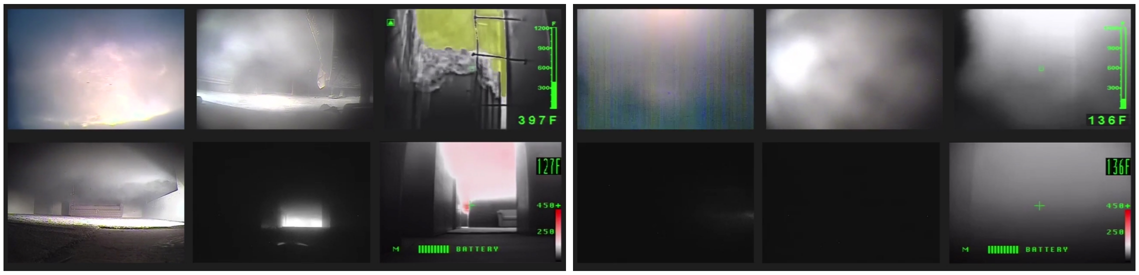
(a) Experiment 7 (b) Experiment 9

Figure 6.76: Post-suppression comparison of bedroom Experiments 7 and 9, with closed door.

(a) Experiment 12 (b) Experiment 13

Figure 6.77: Post-suppression comparison of bedroom Experiments 12 and 13, with open door and windows.

Video and thermal images from the closed door experiments in Figure 6.78a at 240 s after ignition show bedroom 1 was post-flashover with flames on the floor, there was a high energy smoke flow from bedroom 1 into the hallway, and there was a hot gas layer in the living room within 1 m (3.3 ft) of the floor. Figure 6.78b shows the conditions in the same locations 2 min later. There was less burning in bedroom 1, there was less heat as seen by the thermal imagers, and the structure was filled with smoke from the ceiling down to the floor.



(a) Experiment 7, 240 s

(b) Experiment 7, 360 s

Figure 6.78: Video and infrared images for the bedroom Experiment 7, closed door. The three upper views in each set of images are from left to right: bedroom of fire origin, bedroom 2 to the hall outside of bedroom 1, and thermal image of hall outside of bedroom 1 doorway. The lower three views from the left include a living room view looking toward the bedroom hall, and a pair of video and thermal images from cameras in the dining room looking into the living room.

Video images of the exterior of the single story structure taken during Experiment 7, at the same times as the interior images were taken, are shown in Figure 6.79. In the pair of images on the left, smoke was flowing out of the structure around the edges of the closed front door and the closed bedroom window shutters. In the images on the right, captured two minutes later, the smoke out of the structure had stopped.

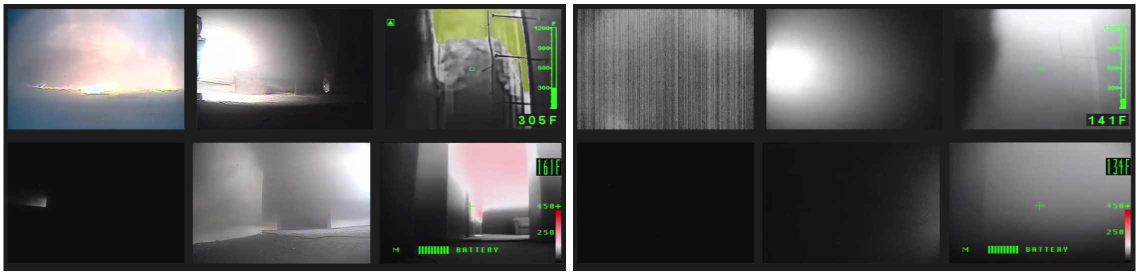
(a) Experiment 7, 240 s after ignition

(b) Experiment 7, 360 seconds after ignition

Figure 6.79: Images of the exterior of the structure for bedroom Experiment 7, closed door. The left view shows the front side. The right view shows the back side.

Experiment 9 was conducted as a replicate to Experiment 7. Although the time of fire development was different between the two experiments, Figure 6.80 shows two sets of images of the same locations as shown in Experiment 7, but captured at 330 s after ignition and then 2 min later at 450 s after ignition. The images are similar to those from Experiment 7.

Given the similar behavior between Experiments 7 and 9 on the interior images, it comes as no surprise that the exterior images from Experiment 9 (see Figure 6.81) are also similar to those from Experiment 7. As the fire was growing and burning post-flashover, the pressure within the closed structure was building. This pressure increase resulted in smoke flowing out of the gaps and openings to the exterior. Once the fire decreased in heat release rate due to a decrease in oxygen available for combustion, the gases inside the structure cooled and the pressure inside the structure decreased. As a result, the smoke flow from the interior of the structure to the exterior stopped.



(a) Experiment 9, 330 s

(b) Experiment 9, 450 s

Figure 6.80: Video and infrared images for the bedroom Experiment 9, closed door. The three upper views in each set of images are from left to right: bedroom of fire origin, bedroom 2 to the hall outside of bedroom 1, and thermal image of hall outside of bedroom 1 doorway. The lower three views from the left include a living room view looking toward the bedroom hall, and a pair of video and thermal images from cameras in the dining room looking into the living room.

(a) Experiment 9, 330 s after ignition

(b) Experiment 9, 450 seconds after ignition

Figure 6.81: Images of the exterior of the structure for bedroom Experiment 9, closed door. The left view shows the front side. The right view shows the back side.

Experiment 12 was another fire ignited in bedroom 1. But this time the front door and windows were open, as noted above. The supply of oxygen enabled the fire to continue burn post flashover. Figure 6.82 shows both video and thermal images of the bedroom of fire origin inside bedroom 2 looking toward the hall outside of bedroom 1, and a thermal image of the hall outside of the bedroom 1 doorway. The lower three views in each set show the living room view toward the bedroom hall and a pair of video and thermal images from cameras in the dining room looking into the living room.

Figure 6.83 shows images of the exterior of the single story structure from Experiment 12, which show the front side of the building and a view of both bedroom 1 windows. Looking at both the interior views and the exterior at 160 s after ignition, bedroom 1 has flames from the ceiling down to the floor. Hot gases were exiting bedroom 1. There was fire in the hall and a hot gas layer in the living room. At the same time, flames were exiting both bedroom 1 windows, and black smoke was exiting the upper half of the doorway.

The sets of images on the right were recorded at 200 s after ignition. Notice how the interior conditions changed. Flames were no longer visible in bedroom 1, the hot gas flow out of bedroom 1 in to the hall had cooled, smoke was down to the floor in bedroom 2, the smoke layer in the living room had descended further, and the fire on the burning carpet was spreading to the sofa. Even though the bedroom appeared to have darkened down, flames were still burning out of the bedroom 1 window opening and the smoke flow out of the structure was the same as 40 s earlier. Basically, the increased burning inside the structure created additional fuel inside the structure, which resulted in a fuel-rich or ventilation-limited condition. Excess fuel gases were building up in the structure and only burning where they had sufficient oxygen and heat. In this case, that meant outside of the bedroom windows and near the floor in the hallway and living room.

(a) Experiment 12, 160 s

(b) Experiment 12, 200 s

Figure 6.82: Video and infrared images for the bedroom Experiment 12, open door and windows. The three upper views in each set of images are from left to right: bedroom of fire origin, bedroom 2 to the hall outside of bedroom 1, and thermal image of hall outside of bedroom 1 doorway. The lower three views from the left include a living room view looking toward the bedroom hall, and a pair of video and thermal images from cameras in the dining room, looking into the living room.

(a) Experiment 12, 160 s after ignition

(b) Experiment 12, 200 seconds after ignition

Figure 6.83: Images of the exterior of the structure for bedroom Experiment 12, open door and windows. The left view shows the front side. The right view shows the back side.

6.2.2 Two Story Structure

Five experiments were conducted using the two-story tall family room as the room of fire origin in the open floor plan colonial style structure. Each experiment differed by a change in ventilation at the time of ignition. As with the experiments in the single story structure, each experiment was started with fresh gypsum wallboard painted with latex paint. A new plywood sub-floor was installed in rooms of origin, target rooms, and areas near open vents. In furnished rooms, the sub-floor was covered with polyurethane foam padding, and 100% olefin carpeting. New furnishings and interior wood doors were installed if damaged.

Experiment 1 served as the baseline case with all of the exterior door and window openings closed. On the lower level, the doors to the den and the laundry room were kept closed. The den and the laundry room were closed for all of the experiments where the fire was started in the family room. On the upper level, the door to bedroom 1 was open, while the doors to bedrooms 2, 3, and 4 were closed. The majority of oxygen available for combustion during this experiment was limited to the oxygen contained within the rooms open to the family room.

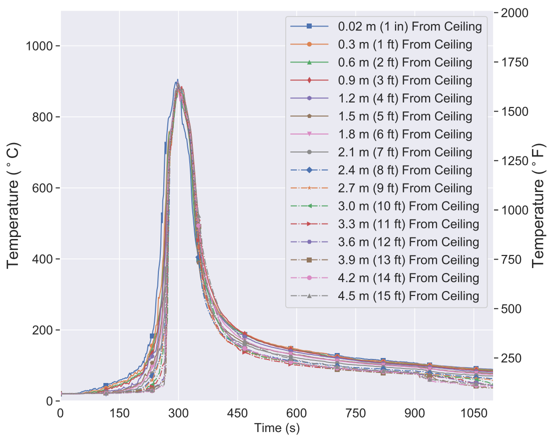
Experiment 2 had the same bedroom door configuration as Experiment 1, but in this experiment the front door was left open at the time of ignition. Air flow in through the front door was available to supply oxygen to the fire throughout the duration of the experiment. With the front doorway being the only vent to the exterior, bi-directional flow was expected. So, the portion of the doorway available as an air intake was of interest to measure, as was the line of demarcation from soot on the entry foyer wall. The open area of the front doorway was 1.80 m^2 (19.3 ft^2).

Experiment 3 added ventilation upstairs by opening the door and window to bedroom 3 prior to ignition. The door to bedroom 1 remained open, while the doors to bedrooms 2 and 4 remained closed. This provided opportunity for some of the fire gases to exhaust through the bedroom 3, as well as potential for fresh air to enter the window. The open area of the bedroom 3 doorway was 1.54 m^2 (16.70 ft^2), and the open area of the bedroom 3 window was 2.58 m^2 (27.78 ft^2).

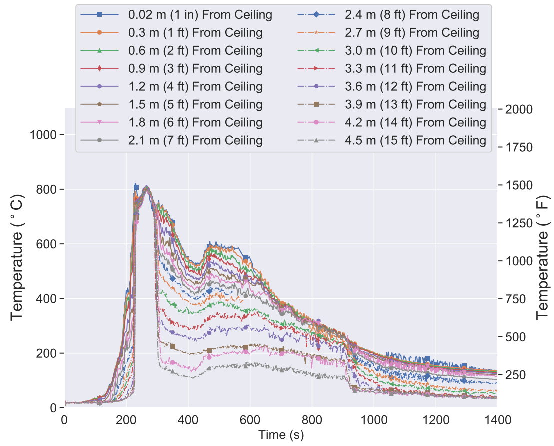
In Experiment 4, additional ventilation was added to the upper level. The door and window to bedroom 3 was closed, but the doors and windows from bedrooms 2 and bedrooms 4 were opened for the duration of the experiment. This provided an opportunity for the hot gases to exhaust from two separate exhaust vents to the exterior. The bedroom doors each had an open area of 1.54 m^2 (16.70 ft^2). The bedroom 2 window opening was 1.24 m^2 (13.35 ft^2) and the bedroom 4 window opening was 2.58 m^2 (27.78 ft^2).

The last experiment that used the family room as the area of origin was Experiment 8. In this case, additional ventilation was added close to the seat of the area of origin. The ventilation configuration was the same as Experiment 2 with the front door open and bedrooms 2 through 4 closed, with the exception that the family room window closest to the ignition sofa was open for the duration of the experiment. The family room window opening was 2.58 m^2 (27.78 ft^2).

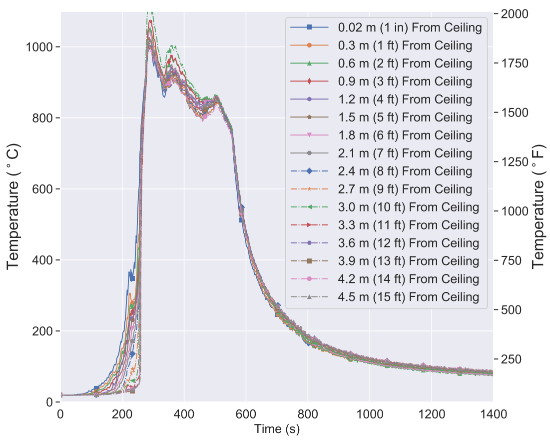
Comparing the temperatures in the family room for each of the above experiments provides a means of estimating the time and duration of peak burning. Figure 6.84 shows the temperature time histories for Experiments 1 through 4 and Experiment 8. Comparing the oxygen concentrations at points in the family room and near the front door for each of the experiments provides another means of examining where the fire was consuming oxygen. Figures 6.85 and 6.86 show the oxygen concentration histories at 1.2 m (4 ft) above the floor and 0.1 m (4 in.)above the floor, respectively, for Experiments 1 through 4 and Experiment 8.



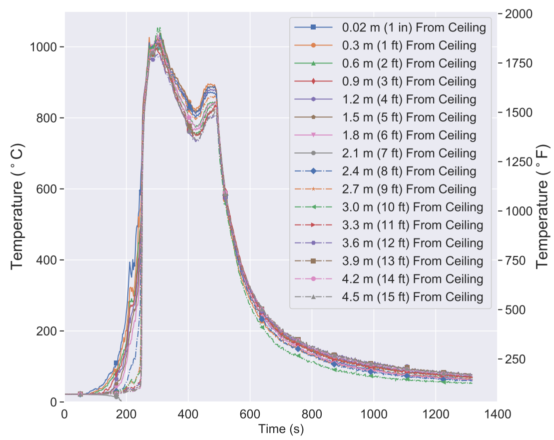
(a) Exp. 1 No Open Vents



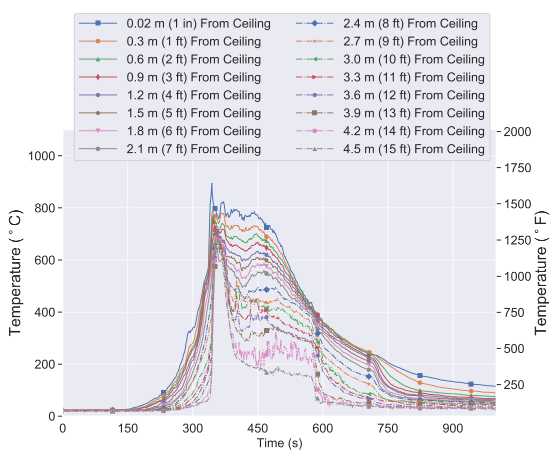
(b) Exp. 2 Open Front Door



(c) Exp. 3 Open Front Door & Bedroom 3 Window

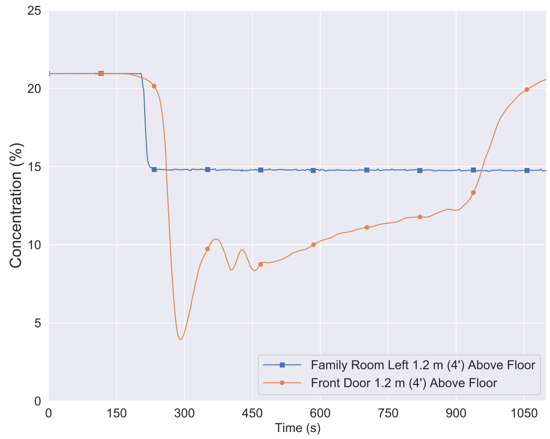


(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows

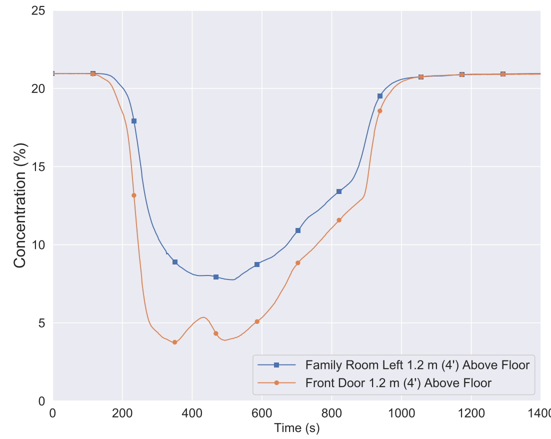


(e) Exp. 8 Open Front Door & Family Room Window

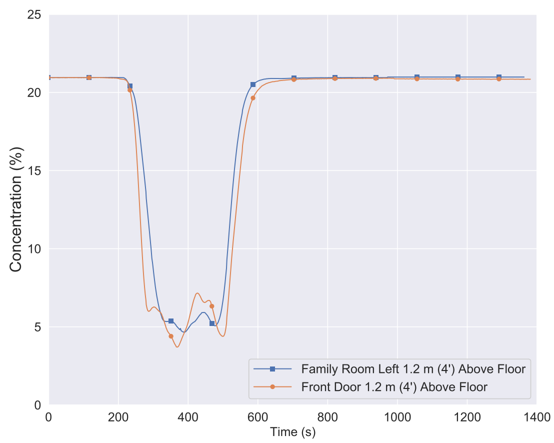
Figure 6.84: Experiments 1–4 and 8, family room center temperature comparison.



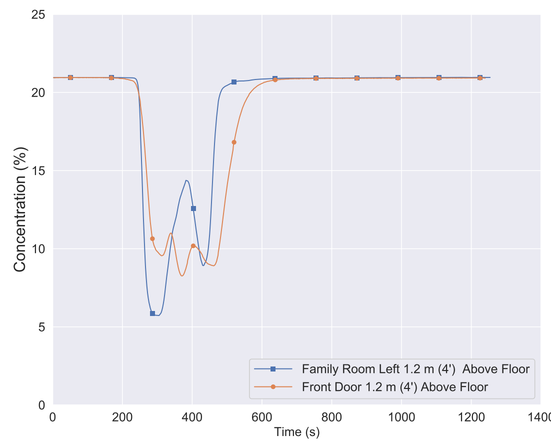
(a) Exp. 1 No Open Vents



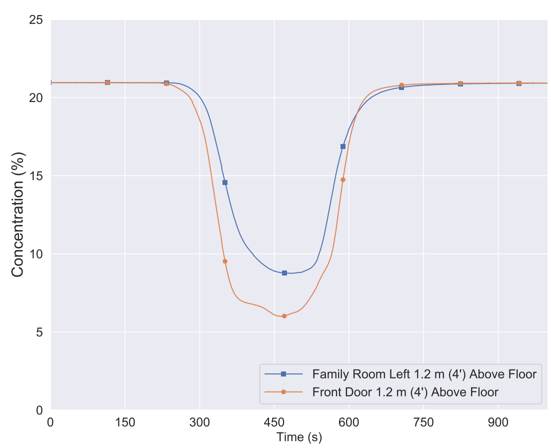
(b) Exp. 2 Open Front Door



(c) Exp. 3 Open Front Door & Bedroom 3 Window

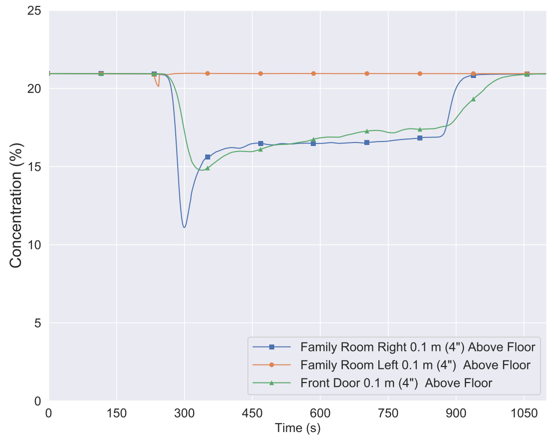


(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows

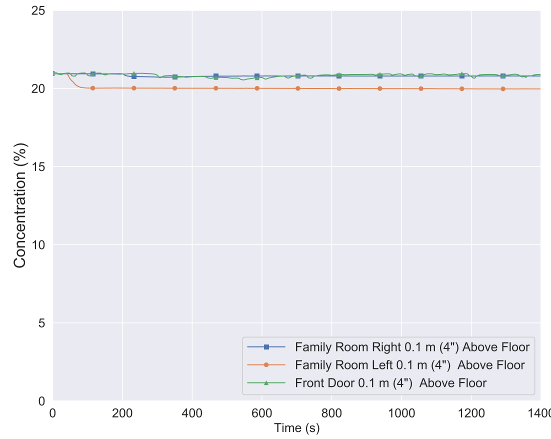


(e) Exp. 8 Open Front Door & Family Room Window

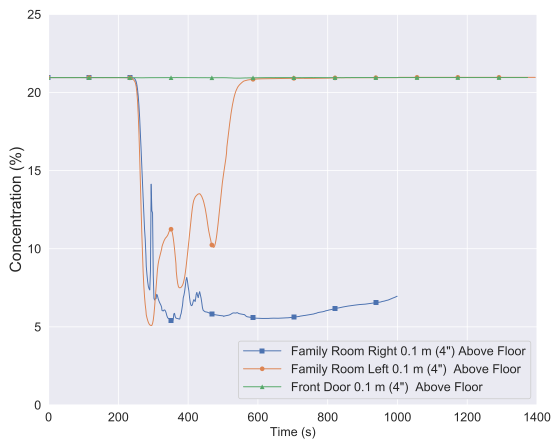
Figure 6.85: Experiments 1–4 and 8, oxygen at 1.2 m above the floor comparison.



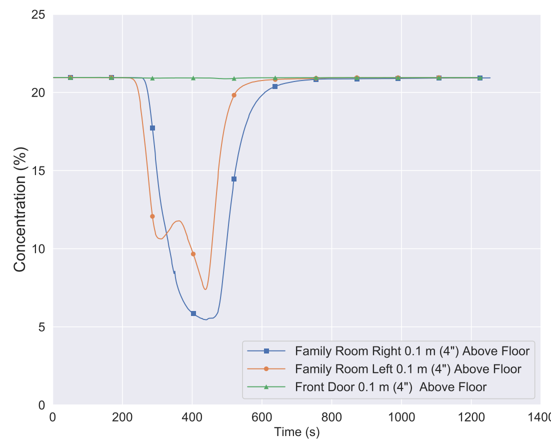
(a) Exp. 1 No Open Vents



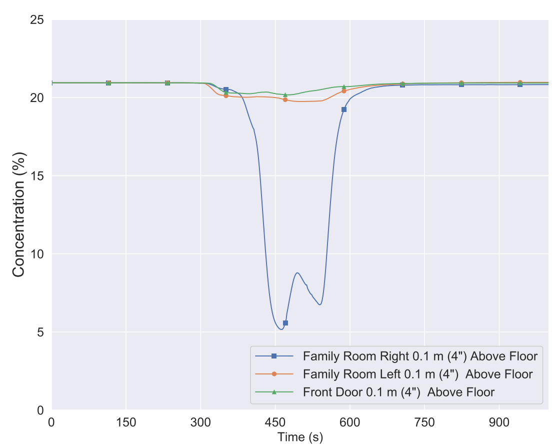
(b) Exp. 2 Open Front Door



(c) Exp. 3 Open Front Door & Bedroom 3 Window



(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows



(e) Exp. 8 Open Front Door & Family Room Window

Figure 6.86: Experiments 1–4 and 8, oxygen at 0.1 m above the floor comparison.

In Experiment 1, the temperatures in the living room (see Figure 6.84a) increased rapidly and reached conditions consistent with a transition through flashover (i.e., the change from a two layer environment to a well mixed single layer environment with temperatures in excess of 600 °C (1112 °F)), and then just as quickly the temperatures decreased.

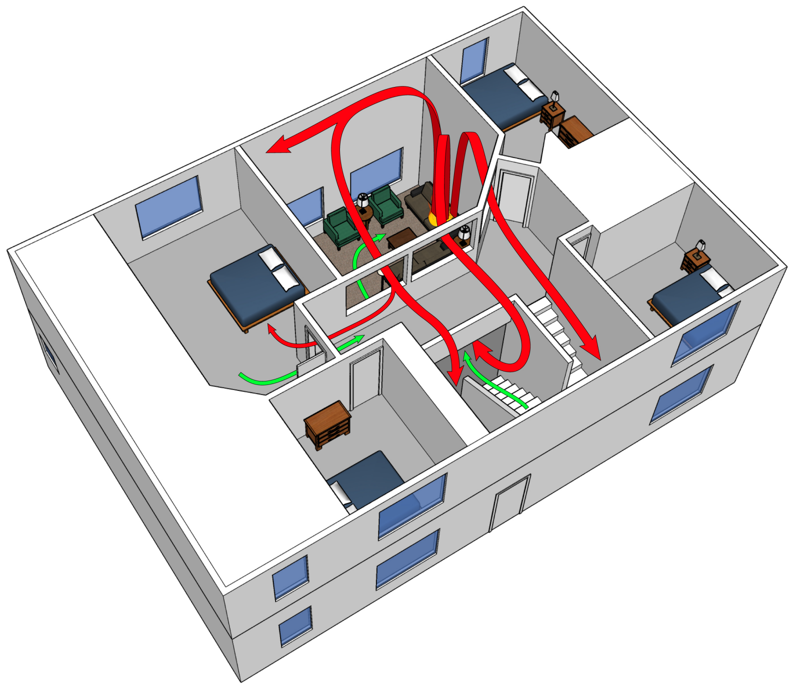


Figure 6.87: Drawing of the pre-flashover flows within the colonial structure, family room fire with closed doors and windows.

The fire damage was limited to the to the right side (closest to the area of origin) of the family room. As the temperatures were increasing and the hot gas layer descended, the oxygen concentrations started to decrease at 1.2 m (4 ft) above the floor position, and then the oxygen sampling points 0.1 m (4 in.) above the floor showed a decrease. As the combustion stopped, the oxygen concentrations started to increase. In this experiment, the fire self-extinguished due to a lack of oxygen. The pre-flashover and post-flashover flows within the structure are represented by Figure 6.87 and Figure 6.88. The pre-flashover drawing shows how the plume of hot gases (see red arrows) impacted the ceiling of the family room and spread across the hallway into the foyer and then down the front side of the structure. The oxygen-laden fresh air (see green arrows) was displaced from the upper level of the structure as well as areas adjoining the family room. The post-flashover drawing represents the two-story structure with self-extinguished fire, and areas open to the family room were filled with smoke. The structure held the smoke even though the heat had dissipated. There were no fire-driven flows, although some low-velocity convective flows were likely occurring within the building.

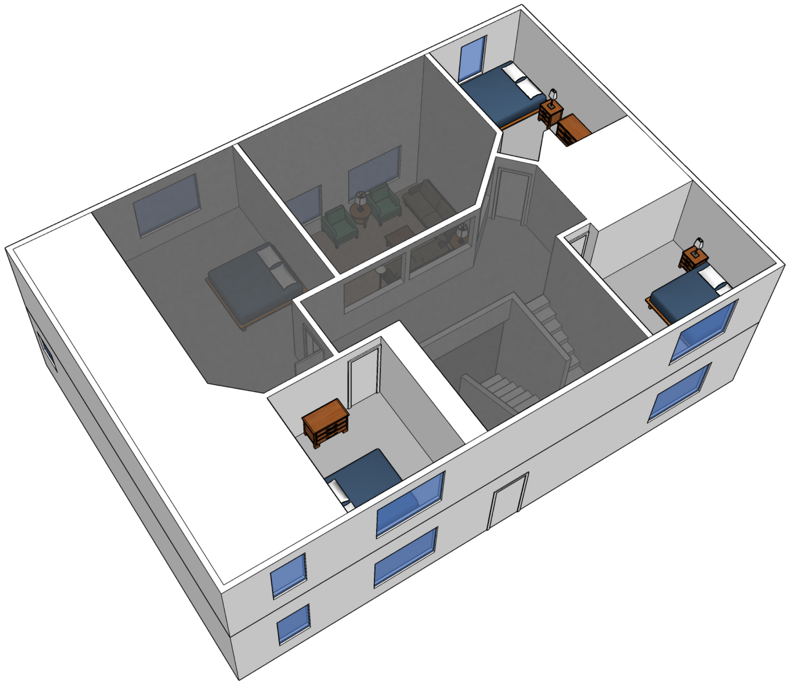


Figure 6.88: Drawing of the post-flashover flows within the colonial structure, family room fire with closed doors and windows.

The temperature time histories in Figure 6.84b show that Experiment 2 had a similar temperature increase and transition to flashover as Experiment 1. However, post-flashover, the temperature time histories from Experiments 1 and 2 diverge. The air supply from the front door in Experiment 2 provided enough oxygen to maintain a smaller amount of combustion than what was needed to maintain equally high temperatures from the ceiling down to the floor. Oxygen concentrations remained near ambient at the three measurement points near the floor (see Figure 6.84b), while the oxygen concentrations were below 10% at the sampling locations 1.2 m (4 ft) above the floor as shown in Figure 6.85b. The gas flows within the structure for Experiment 2 appear in for the pre-flashover flow paths in Figure 6.89 and for the post-flashover flow paths in Figure 6.90. Similar to Experiment 1, the fresh air in the areas open to the fire room on the upper level was displaced by the hot fire gases and forced down to the lower level. Oxygen from the upper level and from the front door was able to reach the family room at the levels closer to the floor.

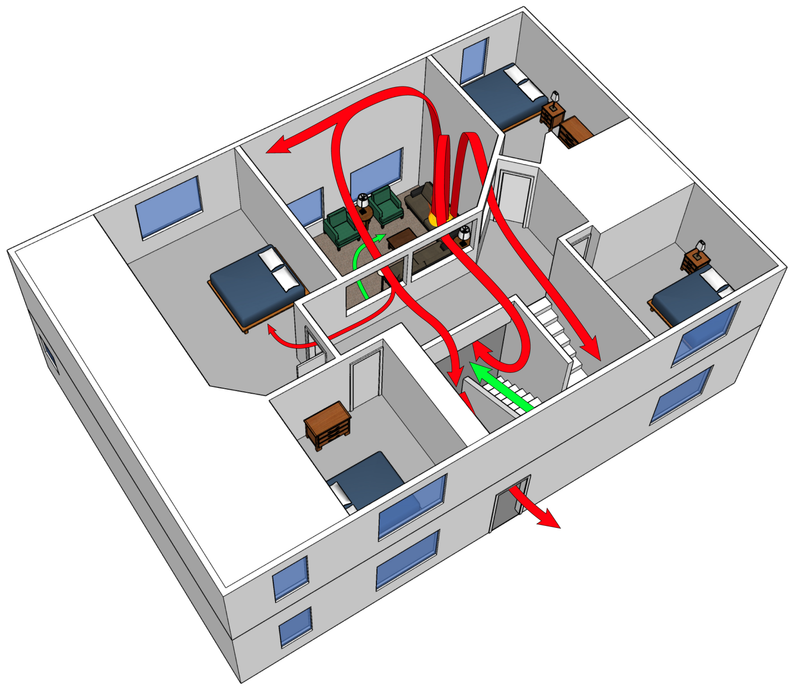


Figure 6.89: Drawing of the pre-flashover flows within the colonial structure, family room fire with open front door.

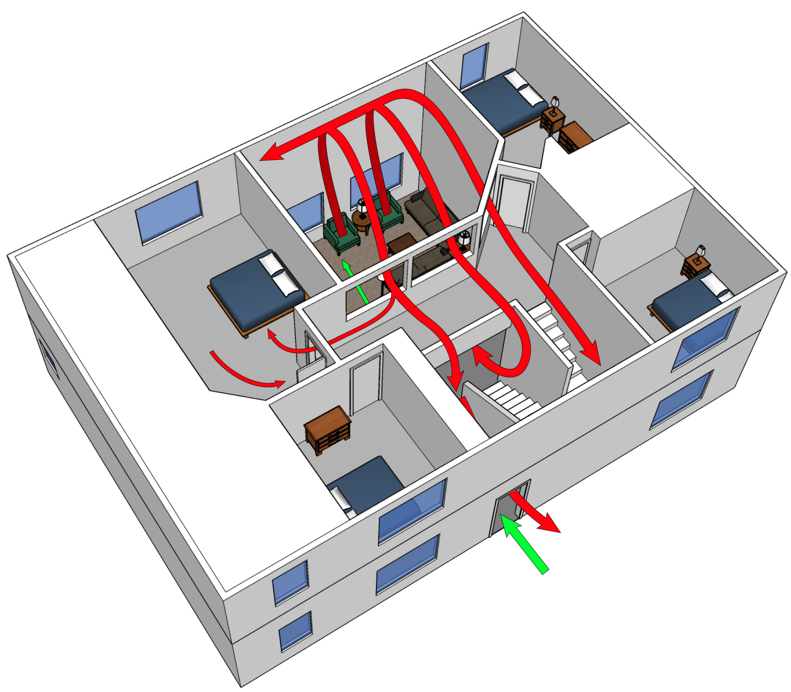


Figure 6.90: Drawing of the post-flashover flows within the colonial structure, family room fire with open front door.

Experiments 3 and 4 (see Figure 6.84c and Figure 6.84d) both had vents on the upper level that were nearly equal in area to the open front door or larger. As a result, less of the front door opening was needed as an exhaust vent and more of the doorway was used as an air intake vent. This allowed the fire in both of these experiments to maintain a higher heat release rate for a longer period of time than the other three experiments. Looking at the oxygen concentration measurements taken at 1.2 m (4 ft) above the floor in Figure 6.85c and Figure 6.85d, the values are approximately 5% for Experiment 3 (one open door and window on the upper level) and approximately 10% for Experiment 4 (two open doors and windows on the upper level). The oxygen concentration values at the 0.1 m (4 in.) above the floor measurement locations dropped roughly 5% in both of these experiments, with the exception of the oxygen sampling location in the foyer near the open front door. At the front door location, the oxygen levels remained at approximately 21% throughout the duration of the fire as shown in Figure 6.86c and Figure 6.86d.

In Experiment 1, the temperatures in the living room (see Figure 6.84a) increased rapidly and reached conditions consistent with a transition through flashover (the change from a two layer environment to a well mixed single layer environment with temperatures in excess of 600 °C (1112 °F)), and then just as quickly the temperatures decreased. The fire damage was limited to the right side (closest to the area of origin) of the family room. Examining the oxygen concentrations, we see that as the temperatures were increasing and the hot gas layer descended, the oxygen concentrations started to decrease at 1.2 m (4 ft) above the floor and then the oxygen sampling points 0.1 m (4 in.) above the floor showed a decrease. As the combustion stopped, the oxygen concentrations started to increase. In this experiment, the fire self-extinguished due to a lack of oxygen. The pre-flashover and post-flashover flows within the structure are appear in Figures 6.87 and 6.88. The pre-flashover drawing shows how the plume of hot gases (red arrows) impacted the ceiling of the of family room and spread across the hallway into the foyer and then down the front side of the structure. The oxygen-laden fresh air (green arrows) was displaced from the upper level of the structure as well as areas adjoining the family room. The post-flashover drawing represents the two-story structure with self-extinguished fire, and areas open to the family room were filled with smoke. The structure held the smoke even though the heat had dissipated. There were no fire-driven flows, although some low-velocity convective flows were likely occurring within the building.

The temperature time histories in Figure 6.84b show that Experiment 2 had a similar temperature increase and transition to flashover as Experiment 1. However, post-flashover, the temperature time histories from Experiments 1 and 2 diverge. The air supply from the front door in Experiment 2 provided enough oxygen to maintain a smaller amount of combustion than what was needed to maintain equally high temperatures from the ceiling down to the floor. Oxygen concentrations remained near ambient at the three measurement points near the floor (see Figure 6.84b), while the oxygen concentrations were below 10% at the sampling locations 1.2 m (4 ft) above the floor (see Figure 6.85b). The gas flows within the structure for Experiment 2 appear in the pre-flashover flow paths in Figure 6.89 and for the post-flashover flow paths in Figure 6.90. Similar to Experiment 1, the fresh air in the areas open to the fire room on the upper level was displaced by the hot fire gases and forced down to the lower level. Oxygen from the upper level and from the front door was able to reach the family room at the levels closer to the floor.

Experiments 3 and 4 (Figures 6.84c and 6.84d both had vents on the upper level that were nearly equal in area to the open front door or larger. As a result, less of the front door opening was needed as an exhaust vent and more of the doorway could be used as a air intake vent. This allowed the fire in both of these experiments to maintain a higher heat release rate for a longer period of time than the other three experiments. Looking at the oxygen concentration measurements taken at 1.2 m (4 ft) above the floor in Figures 6.85c and 6.85d the values are approximately 5% for Experiment 3 (one open door and window on the upper level) and approximately 10% for Experiment 4 (two open doors and windows on the upper level). The oxygen concentration values at the 0.1 m (4 in.) above the floor measurement locations dropped to near 5% in both of these experiments, with the exception of the oxygen sampling location in the foyer, near the open front door. At the front door location, the oxygen levels remained at approximately 21% throughout the duration of the fire.

With regard to the flow paths, Experiment 3 demonstrated three different flow conditions. The first was the pre-flashover condition, where the strongest flow at the front door was air intake while the heated gases filled the upper level and started to exhaust out of the bedroom 3 window, as shown in Figure 6.91.

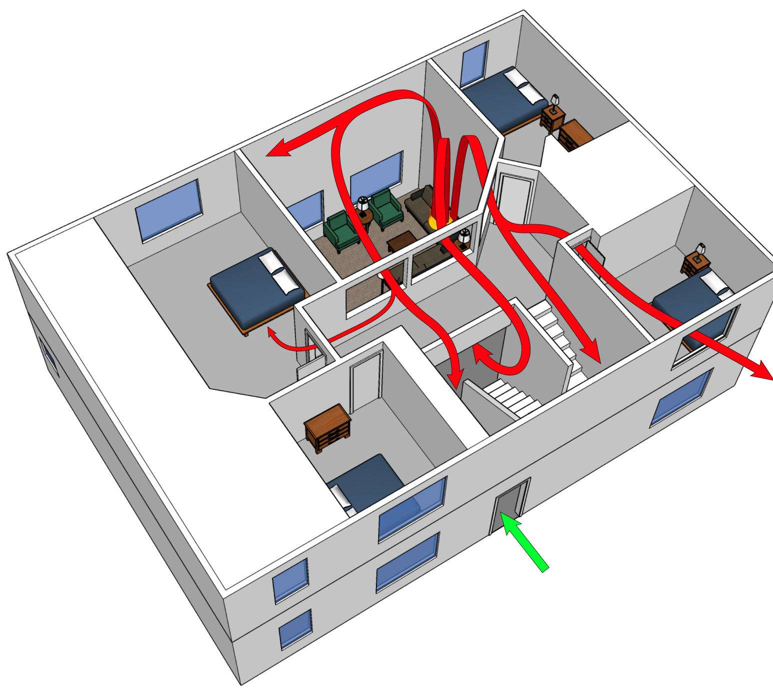


Figure 6.91: Drawing of the pre-flashover flows within the colonial structure family room fire with open front door, bedroom 3 door and window.

As the fire reached flashover in the family room with temperatures at approximately 800 °C (1472 °F) and climbing, the hot gases were expanding so rapidly that for a short time the front door became a uni-directional exhaust vent. The exhaust flow filled almost all of the front door with average peak velocities of approximately 6 m/s (13 mph). Figure 6.92 represents this condition qualitatively based on temperature, velocity, pressure, and oxygen data recorded at 270 s after ignition. Post-flashover (see Figure 6.93) the front door became a bi-directional vent with the higher pressure hot smoke exiting near the top of the doorway, while the rest of the open doorway served as an air intake. Additional recirculation took place on the second story. Similar flow behavior also occurred in Experiments 2 and 4.

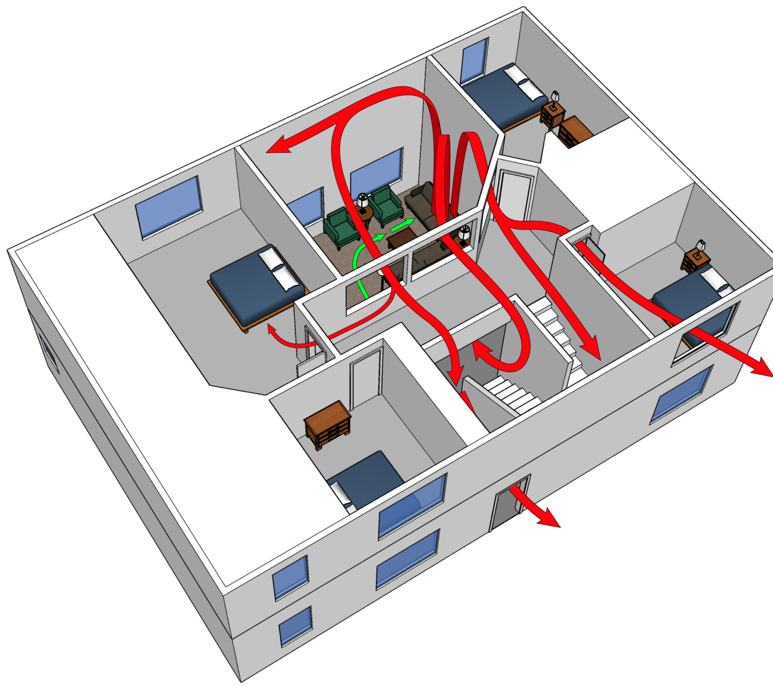


Figure 6.92: Drawing of the post-flashover flows within the colonial structure, family room fire with open front door bedroom 3 door and window at 285 s after ignition.

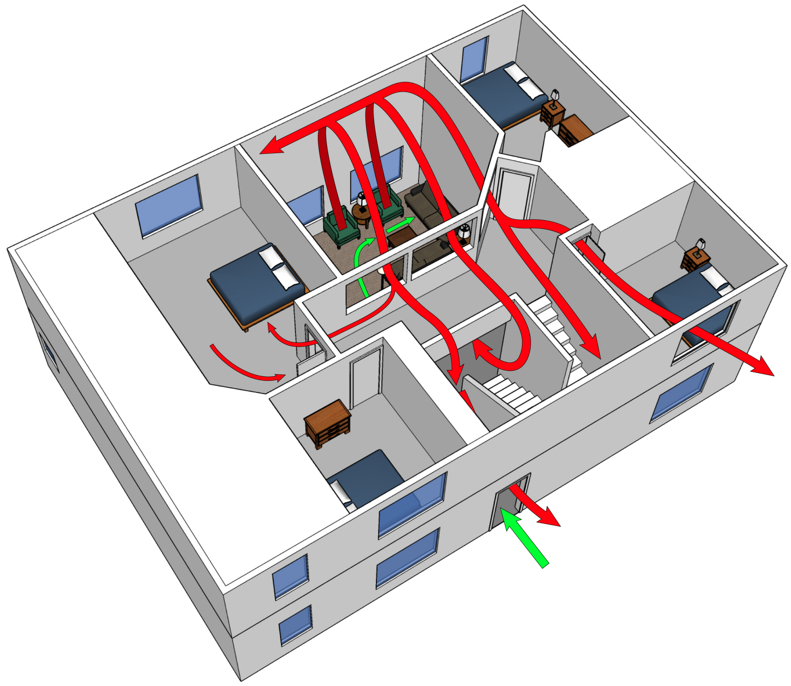


Figure 6.93: Drawing of the post-flashover flows within the colonial structure, family room fire with open front door bedroom 3 door and window at 400 s after ignition.

Figure 6.94 highlights the pre-flashover flows in the structure for Experiment 4 while Figure 6.95 shows the post-flashover flows within the structure. The pre-flashover drawing shows how the plume of hot gases (see red arrows) impacted the ceiling of the family room and spread across the hallway into the open bedrooms and out their respective open windows, as well as into the foyer and then down the front side of the structure. The oxygen-laden fresh air (see green arrows) was pulled in from the open windows, but being remote from the fire it was less significant than the air pulled in through the open door. The post-flashover drawing (see Figure 6.95) shows that the front door became a bi-directional vent with the higher pressure hot smoke exiting near the top of the doorway, while the rest the open doorway served as an air intake. The windows had transitioned to be primarily exhaust vents, and additional recirculation took place on the second story.

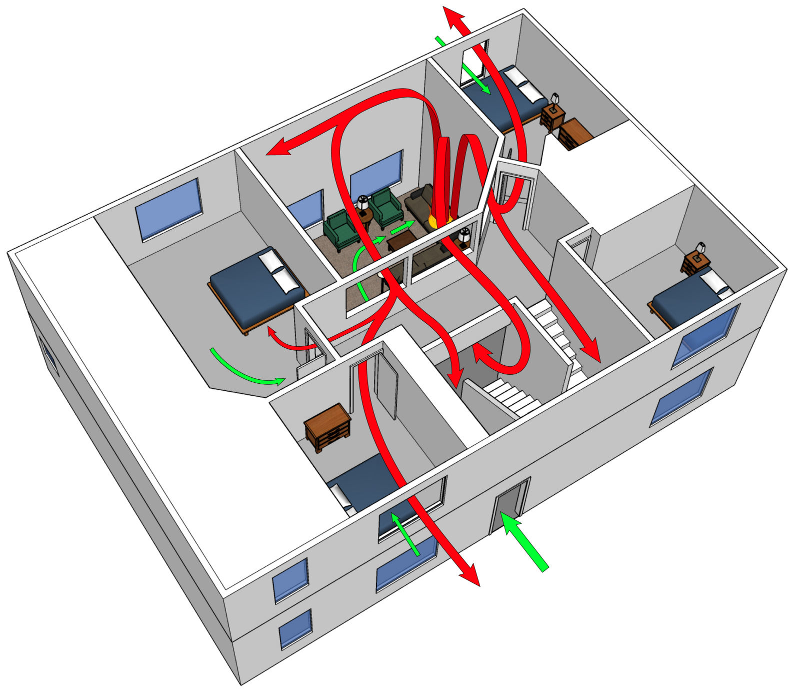


Figure 6.94: Drawing of the pre-flashover flows within the colonial structure family room fire with open front door, bedroom 3 and 4 doors and windows.

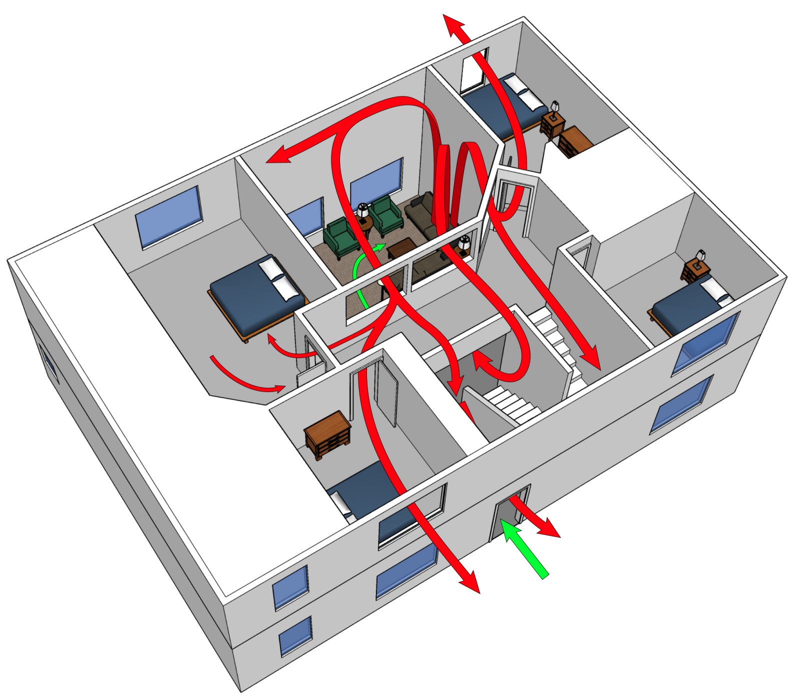


Figure 6.95: Drawing of the post-flashover flows within the colonial structure family room fire with open front door, bedroom 3 and 4 doors and windows.

Figure 6.96 highlights the pre-flashover flows in the structure for Experiment 8. During the fire growth stage prior to flashover, both the front door and family room window served as a bi-directional vent. The open family room window, close to the area of origin, in conjunction with the open front door, appeared to slow the increase in temperatures in the family room and slow down the transition to flashover (see Figure 6.84e). Similar to Experiment 2, post-flashover the temperatures throughout the family room re-stratified. The post-flashover oxygen levels at the 1.2 m (4 ft) above the floor locations were below 10%, which was also similar to Experiment 2. The oxygen sampling locations positioned 0.1 m (4 in.) above the floor near the front door and in the family room remote from the area of origin also had similar readings for both Experiments 2 and 8 of approximately 20%. The exception was the low sampling location near the area of fire origin – in that case the minimum measured oxygen concentration was close to 5%. The post-flashover flow diagram appears in Figure 6.97. The fire in the family room continued to burn post-flashover with the window close to the area of origin serving primarily as an exhaust vent, while the open front doorway served as a bi-directional vent.

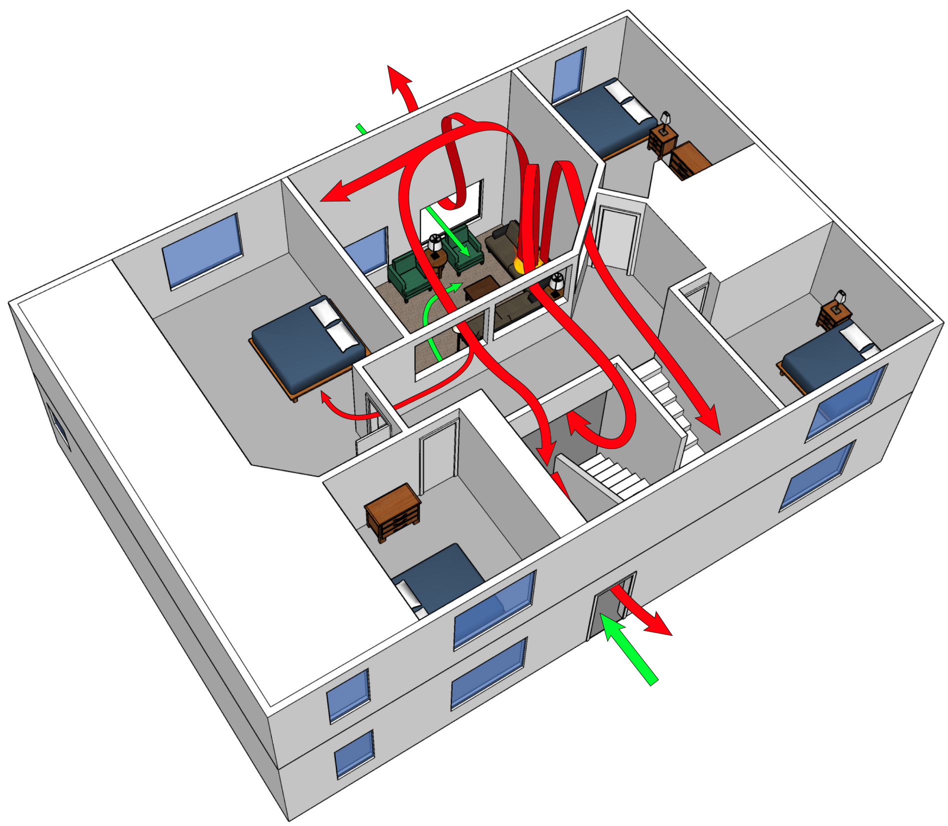


Figure 6.96: Drawing of the pre-flashover flows within the colonial structure family room fire with open front door and family room window.

The temperature and oxygen time histories demonstrated differences in the fire behavior based on changes to the ventilation configurations. Unfortunately, the fire investigator will not have access to this type of data at a typical fire scene. So, the connection between the flow paths, oxygen availability (both pre-flashover and post-flashover), fuel availability, and heat needs to be made

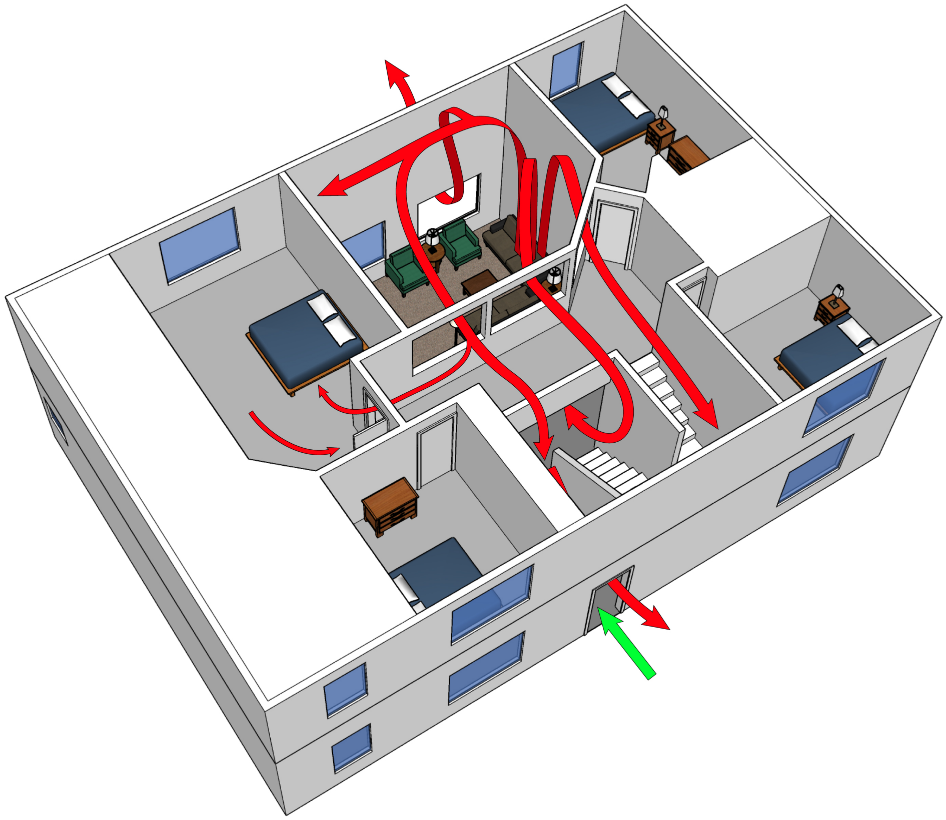


Figure 6.97: Drawing of the post-flashover flows within the colonial structure family room fire with open front door and family room window.

to the damage caused by the fire. Understanding the impact of changes in ventilation on the fire damage patterns inside the structure will provide the fire investigators with knowledge to assess the patterns using a fire dynamics based analysis method such as the Origin Matrix Method presented by Cox [24].

Foyer Fire Damage Comparisons

The front door was a key vent for four of the five different ventilation configurations used with the family room fires. On the foyer wall just to the right of the front door as you would enter the house, a line of demarcation, typically from condensed soot, was generated by each of the experiments. Figure 6.98 contains a post-fire image from each of the family room experiments.

In Experiment 1, all of the exterior vents were closed. In this experiment smoke was exiting under pressure around the edges of the closed front door. Soon after smoke had exited the bottom gap of the door, all of the smoke flow from around the door stopped. This corresponded with the decrease in gas temperature and pressure throughout the structure. Figure 6.98a shows that soot had condensed on the foyer wall down to within 0.15 m (6 in) of the floor.

In Experiment 2, the open front doorway was the only vent. On the stair wall of the foyer between the front doorway and the oxygen sampling tubes, the line of demarcation was between 0.48 m and 0.61 m (19 in and 24 in) above the floor.

Experiment 3 added an open bedroom door and window on the upper level of the house. The additional ventilation resulted in an arched-shaped line of demarcation on the stair wall of the foyer. The lines generated in Experiments 1 and 2 were more horizontal. Between the oxygen sampling tubes and the front doorway, the height of the soot line varied from approximately 1.0 m (3.2 ft) to 0.30 m (1.0 ft) above the floor. It is important to note that thermal damage to the painted gypsum wall board was evident in some locations on the wall above the line of demarcation. In Experiments 1 and 2, there was no evidence of thermal damage on the wall.

Experiment 4 added another open bedroom door and window to the ventilation configuration of Experiment 3. This resulted in the line of demarcation moving up, less of a visible accumulation of soot on the wall, and an increase in thermal damage to portions of the wall. The lowest point of the soot line of demarcation was near the intersection of the foyer stair wall and the front wall of the structure next to the open doorway and it was approximately 0.70 m (2.3 ft) above the floor. The lowest point of thermal damage, to paint and paper, was approximately 0.83 m (2.7 ft) above the floor.

The upper level vents were closed for Experiment 8, and the family room window closest to the ignition sofa was opened along with the front door. This resulted in a flattening of the condensed soot line on the foyer wall and a reduction in thermal damage. Between the oxygen sampling tubes and the front wall, the height of the line of demarcation varied from 0.61 m (2.0 ft) to 0.43 m (1.4 ft).

While conditions at the front door changed through the development of each fire, it would appear that the post-flashover conditions had the most impact on the soot deposition and thermal damage.

(a) Exp. 1 No Open Vents

(b) Exp. 2 Open Front Door

(c) Exp. 3 Open Front Door & Bedroom 3 Window

(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows

(e) Exp. 8 Open Front Door & Family Room Window

Figure 6.98: Experiments 1–4 and 8, line of demarcation in the foyer.

Family Room Fire Damage Comparisons

The family room was approximately 5.80 m (19 ft) across. From the ignition sofa to the counter behind the television stand measure 4.85 m (15.9 ft) deep, and from the back wall of the structure to the support column near the center of the structure measured 4.88 m (16.0 ft) high. The lower level of the family room was bounded by the back wall of the structure, and a 3.15 m (10.3 ft) wall (the ignition sofa wall). The other two sides of the family room ware open to other areas of the structure, including the kitchen, dining room, living room, and the open foyer. The upper portion of the family room had a third wall boundary that was 4.85 m (15.9 ft) long opposite the ignition sofa wall. The other side of the upper portion of the family was open to the rest of the upper level through three large openings to the hallway that connected the bedrooms.

Figures 6.99 and 6.101 feature photographs from the family room fire experiments. The ventilation configuration for each experiment is appears in the sub-caption for each photograph.

(a) Exp. 1 No Open Vents

(b) Exp. 2 Open Front Door

(c) Exp. 3 Open Front Door & Bedroom 3 Window

(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows

(e) Exp. 8 Open Front Door & Family Room Window

Figure 6.99: Experiments 1–4 and 8, fire damage in the family room, area of origin.

The fire damage near the area of fire origin appears in Figure 6.99. As additional vents remote from the fire area of origin were added, the extent of the fire damage increased as shown in Figures 6.99a through 6.99d. The increases in damage included all portions of the fire origin area, including the ceiling, the walls, the floor, and the furnishings.

In Experiments 1 through 4, a clean burn plume pattern can be observed behind the right side of the sofa above the point of ignition. Observations were made in the review of the videos to determine when the flame extended beyond the back of the sofa to expose the gypsum wallboard behind and above the sofa. Two other key points in experiment timeline included the time to flashover and the beginning of fire suppression. These three times were used to determine pre-flashover exposure and the post-flashover exposure periods for the gypsum wallboard behind and above the point of ignition. Two of these time values–flame extension above the sofa back and the start of suppression–could be determined with more accuracy than the time to flashover. The time to flashover was identified by flames spreading across the ceiling of the room of origin and the start of rapid horizontal spread of fire (or heat signature in the thermal image) on the carpeting or adjacent furniture. This transition from a two layer environment to single vertical zone of well mixed burning from the ceiling down to the floor occurred over seconds. Keep in mind the flashover times given here could easily have been $\pm$ 10 s.

The plume pattern from Experiment 1 was generated during a 250 s pre-flashover exposure and persisted through a short 30 post-flashover exposure. This experiment had access to air from outside of the structure and the fire self-extinguished.

The plume pattern from Experiment 2 had less pre-flashover time (185 s) and more post-flashover exposure time (670 s) than Experiment 1. The extended post-flashover burn time was due to the open front door, but the fire environment was fuel-rich during the post-flashover burn period. The height of the pattern was similar, but the width of the pattern had increased.

The plume pattern from Experiment 3 had a pre-flashover exposure time of 225 s and a post-flashover exposure time of 315 s. In this case, the plume pattern had increased in height relative to the pattern in Experiment 2. Experiment 3 was the first experiment with a vent above the floor of fire origin. Also notice that a piece of gypsum wallboard installed above the ignition sofa, and another toward the center of the family room, fell off of the ceiling after suppression. Water was not applied to the ceiling.

Experiment 4 had two vents above the floor of fire origin. The plume pattern from Experiment 4 had a pre-flashover exposure time of 170 s and a post-flashover exposure time of 250 s. The plume pattern was wider than any of the plume patterns from the first three family room experiments. The height of the pattern was similar to the height of the pattern in Experiment 3.

The ventilation configuration in Experiment 5 was different than the first four family room experiments. The vents to the exterior in Experiments 2 through 4 were remote from the room of fire origin, and beginning with Experiment 1, they represented a progression from zero exterior vents up to three remote exterior vents. Experiment 5 had two exterior vents, the open front door (remote) and the open family room window adjacent to the ignition sofa. The family room window opening was large, measuring 1.77 m (5.8 ft) wide by 1.45 m (4.8 ft) tall.

The plume pattern from Experiment 8 (see Figure 6.99e) had a pre-flashover exposure time of 220 s and a post-flashover exposure time of 230 s. The pattern appeared to be similar in height and width to the pattern from in Experiment 4. However, the definition of the pattern, while clear to the authors, would be harder to discern than the plume patterns in the previous four experiments. With the vent close to the area of origin, additional clean burn areas were generated in the area of origin that made the plume patter more difficult to distinguish from the surrounding fire damage.

Another interesting occurrence in this experiment was that the pressure from the fire growth closed the front door. As the fire was transitioning to flashover, the pressure increase and the resultant gas velocity through the front doorway caused the front door to swing shut. The fire burned post-flashover for 30 s before a firefighter could get the door open again. Therefore, for 30 s of the post-flashover burn period the only exterior vent was the family room window.

Figure 6.100 features photographs of the family room area of origin to provide a better view of the fire damage on the walls and floor. In Experiment 1, the fire damage to the carpet, padding, and sub-floor plywood was limited to the area bound by the furniture. However, for Experiments 2 through 4 the burning on the floor and the area of the floor burned increased with the increase in ventilation. As a result, it became difficult to separate the burned carpet and padding from the charred plywood sub-floor. In Experiment 2 the carpet burn line of demarcation was half way between the end of the target sofa and the TV stand. In Experiments 3 and 4, almost all of the carpet and padding was burned to some degree. The damage to the floor area in Experiment 8 was similar to the amount of fire damage to the floor in Experiment 1. It was mainly in the furnished area of the family room.

(a) Exp. 1 No Open Vents (b) Exp. 2 Open Front Door

(c) Exp. 3 Open Front Door & Bedroom 3 Window (d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows (e) Exp. 8 Open Front Door & Family Room Window

Figure 6.100: Experiments 1–4 and 8, fire damage in the family room, area of origin after furniture removal.

Figure 6.101 features photographs of the family room area opposite the ignition sofa wall from the five family room experiments. The TV and TV stand were positioned in front of a painted, plywood-sided counter that divided the family room from the kitchen area.

The fire damage from Experiments 1 and 8 consisted of a thermal damage to the TV (melted plastic components) and soot and debris deposition on the wood TV stand. The carpet in front of the TV was not burned, although in Experiment 1 there is evidence of thermal damage on portions of the carpeting due to radiant heat. The damage to the TV in Experiment 2 was similar to that in

Experiment 1. However, in Experiment 2 there was also heat damage to the TV stand in the form of melted plastic components and a condensed soot line of demarcation across the top front drawer and the sides of the stand. The carpeting around the TV stand was not burned.

The fire damage from Experiments 3 and 4 on this end of the family room was similar. Most of the plastic components of the TV have burned away leaving a steel shell. The TV stand was burned and charred, as was the plywood wall next to the TV stand. The carpet, padding and plywood around the TV stand was also burned.

(a) Exp. 1 No Open Vents

(b) Exp. 2 Open Front Door

(c) Exp. 3 Open Front Door & Bedroom 3 Window

(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows

(e) Exp. 8 Open Front Door & Family Room Window

Figure 6.101: Experiments 1–4 and 8, fire damage in the family room, TV and stand.

Figure 6.102 is features photographs that basically show the contrast of the different sections of the plywood counter after the TV and stand were removed. In Experiments 1 and 2 (see Figures 6.102a and 6.102b), the radiant heat from the fire warmed the painted plywood enough so that the soot from the smoke could not condense on the surface. However, the TV stand shielded the plywood counter from the radiant heat, but it could not block the convected smoke flow behind the TV stand. As a result, the smoke flowed over the cooler, protected surface of the plywood counter behind the TV stand and apparently the temperature difference was enough to result in soot deposition behind the TV stand.

(a) Exp.1 No Open Vents

(b) Exp.2 Open Front Door

(c) Exp.3 Open Front Door & Bedroom 3 Window

(d) Exp.4 Open Front Door & Bedroom 2 & 4 Windows

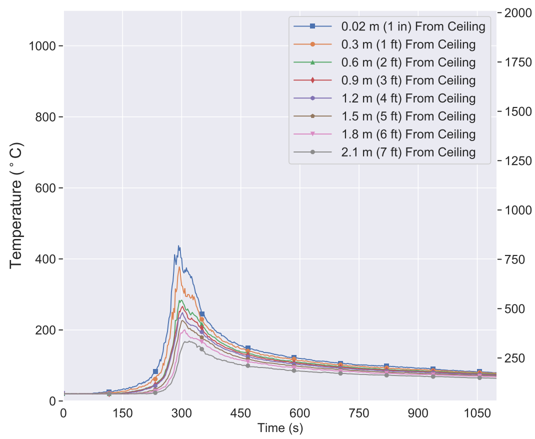
Figure 6.102: Experiments 1–4, fire damage in the family room TV area after removal of furniture.

Figures 6.102c and 6.102d show something different. In these experiments, the exposed plywood on the counter was burned and charred. The protected area behind the TV stand did not burn. It had some soot deposition but not as much as in Experiments 1 and 2. Is it possible the smoke heated the protected area of the counter such that not as much soot was deposited? Both of these experiments had gas temperatures in the family room in excess of 800 °C (1472 °F) from the ceiling to the floor for extended periods of time. Given the increased amount of combustion in the family room, was there less soot available for deposition? Although the back panel of the TV stand did not burn through, did the burning surfaces of the TV stand impact the soot deposition in the protected area?

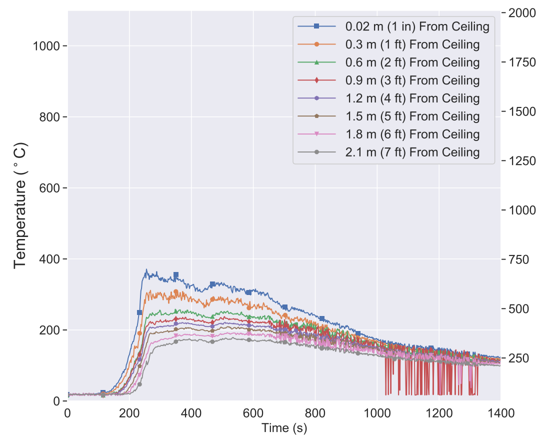
Was it an issue of flow paths? In these two experiments, the front door provided more intake air than it did in Experiments 1 and 2 due to the upper level vents exhausting some of the heat and smoke. Perhaps the convected heat gas flow was predominately up and away from this region of the room due to the ventilation provided on the upper level.

Bedroom 1 Fire Damage Comparisons

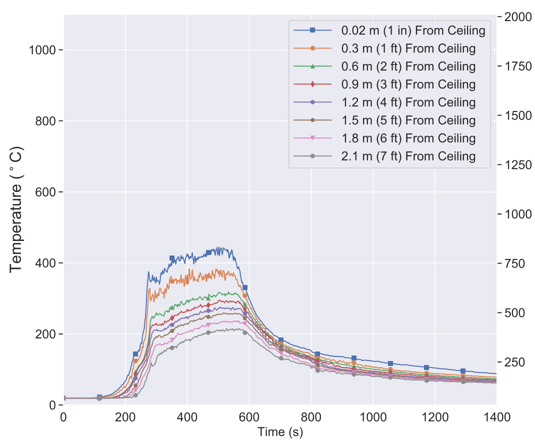
Bedroom 1 was the most remote open area in the family room area of fire origin. The door to bedroom 1 was open during each of the family room experiments. However, there was never a vent open to the exterior from bedroom 1. The temperatures in bedroom 1 can be compared in Figure 6.103. The peak temperatures occurred near the ceiling in each experiment, and the range of the peak temperatures near the ceiling was approximately 350 °C (660 °F) to 470 °C (880 °F). The lowest temperatures were recorded at a position 2.1 m (7 ft) below the ceiling or 0.3 m (1 ft) above the floor. The highest temperatures near the floor ranged from 165 °C (330 °F) to 260 °C (500 °F).



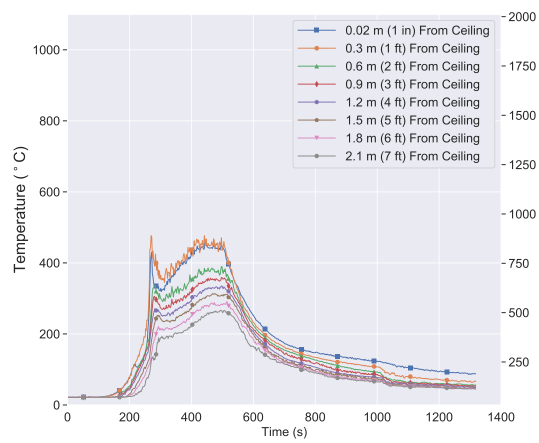
(a) Exp.1 No Open Vents



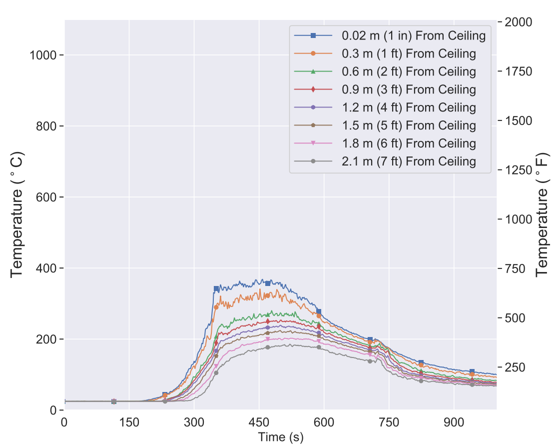
(b) Exp.2 Open Front Door



(c) Exp.3 Open Front Door & Bedroom 3 Window



(d) Exp.4 Open Front Door & Bedroom 2 & 4 Windows



(e) Exp.8 Open Front Door & Family Room Window

Figure 6.103: Experiments 1–4 and 8, bedroom 1 temperature comparison.

The mattress, box spring, and polyurethane pad were covered with a new bed sheet for each experiment. Given the temperature gradient discussed above, no thermal damage occurred to any of the bed components for any of the experiments. As shown in Figure 6.104, soot deposition on the sheets was the extent of the fire damage to the bed.

(a) Exp. 1 No Open Vents

(b) Exp. 2 Open Front Door

(c) Exp. 3 Open Front Door & Bedroom 3 Window

(d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows

(e) Exp. 8 Open Front Door & Family Room Window

Figure 6.104: Experiments 1–4 and 8, bedroom 1 bed post-experiment.

Figure 6.105 shows the amount of fire damage to the door to Bedroom 1 from each of the five experiments. The door was in the open position for each experiment. Experiment 1, with no exterior vents, deposited soot on the door, and there was no thermal damage (see Figure 6.105a). With the open front door in Experiment 2, the upper corner of the door had burned away and the entire face of the door had been covered with soot (see Figure 6.105b), which indicates a fuel-rich condition on the upper level. While the peak temperatures in bedroom 1 were slightly higher for Experiment 1, the duration of the exposure in Experiment 1 was less.

(a) Exp. 1 No Open Vents (b) Exp. 2 Open Front Door

(c) Exp. 3 Open Front Door & Bedroom 3 Window (d) Exp. 4 Open Front Door & Bedroom 2 & 4 Windows (e) Exp. 8 Open Front Door & Family Room Window

Figure 6.105: Experiments 1–4 and 8, bedroom 1 door post-experiment.

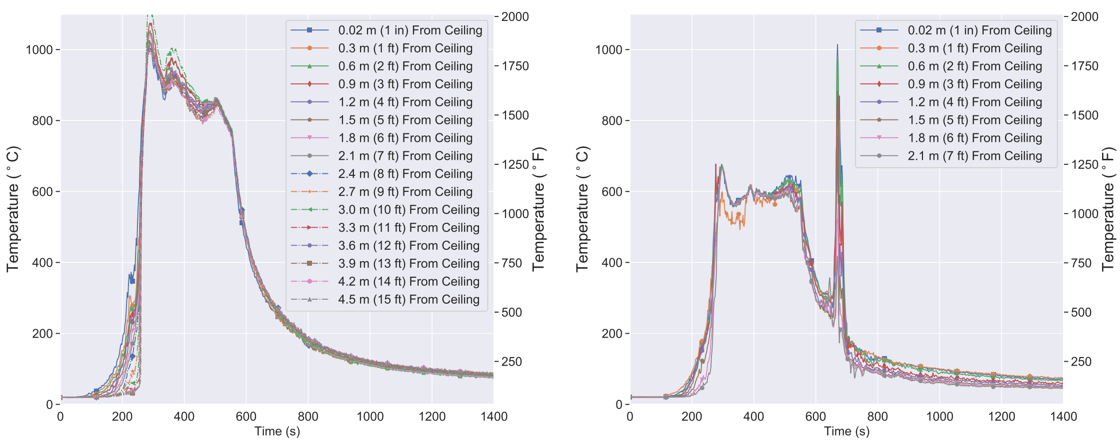
Approximately a third to half of each bedroom 1 door exposed in Experiments 3 and 4 was burned away (see Figures 6.105c and 6.105d). With exhaust vents on the upper level and additional oxygen for combustion entrained through the front door, more flaming combustion was sustained on the upper level. As a result, there was less soot available for deposition on the lower part of the door, and the door was likely heated such that condensation of the soot available was less likely.

Conversely, in Experiment 8, the window closest to the ignition sofa was open. This allowed some of the energy from the fire to exhaust out of the window prior to it reaching the upper level. There was some charring on the door, but no area exhibited a loss of material to the point of penetrating the surface of the door face. Figure 6.105e shows the door had less soot deposition than Experiment 2 but more soot deposition than Experiments 1, 3, and 4.

Bedrooms 2, 3, and 4 Fire Damage Comparisons

Experiments 3 and 4 utilized bedrooms as part of the exhaust portion of the flow path. In each case, the open bedrooms were observed to have flames moving through them, and then had flames burning outside of the windows prior to suppression. In Experiment 3, the door and window in bedroom 3 were open. The doors to bedrooms 2 and 4 were protected with gypsum wallboard and sealed off.

Figure 6.106 includes a comparison of the Experiment 3 temperatures from the family room and the bedroom 3. Both the family room and bedroom 3 had flashed over, based on the idea that a fire room that has just transitioned through flashover will have a single well-mixed combustion zone with temperatures in excess of 600 °C (1112 °F). The temperature spike that occurred after 600 s in bedroom 3 was the result of the interior fire attack. Firefighters had to flow water prior to reaching the seat of the fire in bedroom 3. The environment inside the structure was disturbed and additional air entered the bedroom, which resulted in rapid fire growth until water was applied inside the compartment. In this case the additional burn time was short, but that may not be the case in an actual fire attack. Therefore, it is important for investigators to interview the firefighters at a fire scene, not only to understand what they saw on arrival, but also to understand what tactics were used and how the firefight progressed.

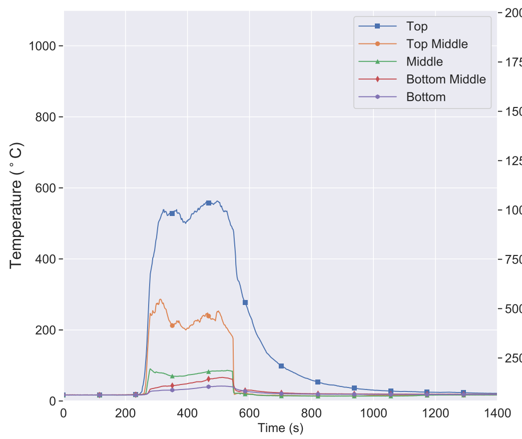


(a) Family Room Temperature

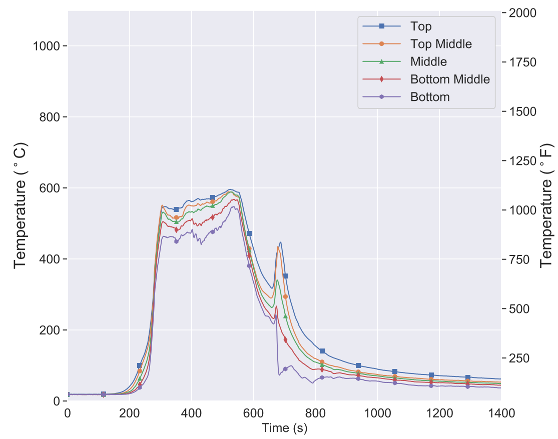
(b) BR 3 Temperature

Figure 6.106: Experiment 3, family room and bedroom 3 temperature comparison.

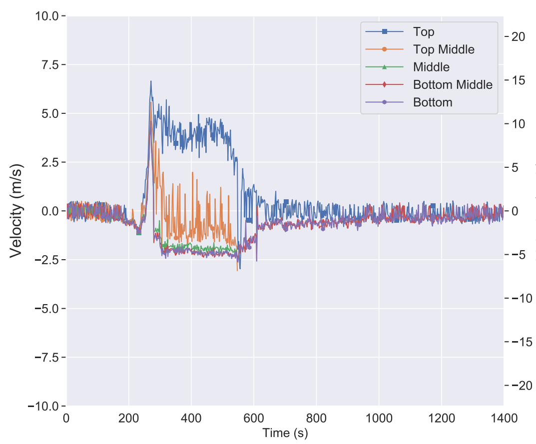
Figure 6.107 includes a comparison of the temperatures and velocities in the open front doorway and the bedroom 3 window. From the doorway temperature and velocity profile, the doorway was a bi-directional vent for most of the post-flashover portion of the fire. More than half of the doorway opening acted as an air intake, so it stands to reason the bedroom window was acting primarily as a unidirectional hot gas exhaust vent.



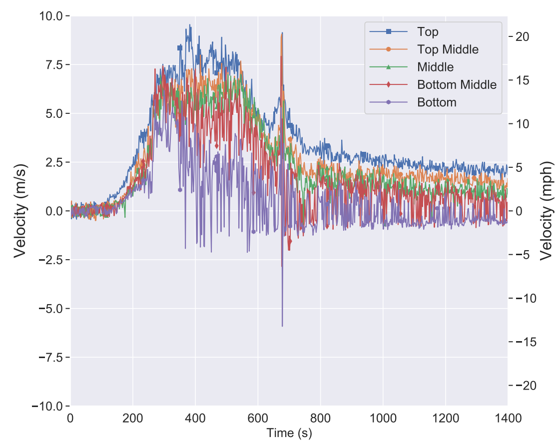
(a) Front Door Temperature



(b) BR 3 Window Temperature



(c) Front Door Velocity



(d) BR 3 Window Velocity

Figure 6.107: Experiment 3, front door and bedroom 3 window comparison.

Post fire-suppression photographs of bedroom 3 appear in Figure 6.108. A significant amount of fuel remained in bedroom 3 at the end of the experiment. Most of the polyurethane foam bed pad was intact, and the plywood floor between the wall and the bed (not in the direct flow path) was exposed but mostly unburned. The wood nightstand and dresser were charred but did not burn through. The corner of the bed close to the window appeared to have burned to a greater extent than the rest of the bed. The lowest gas velocity probe in the bedroom 3 window (see Figure 6.107d) shows that the gas velocity was pulsing from positive (hot gas exhaust) to negative (air intake) at regular intervals starting around 400 s after ignition. Perhaps the air entering low in the window aided in the additional burning on the top layer of the corner of the bed.

In general, the fire damage in bedroom 3 was consistent with post flashover damage. The door to the bedroom was burned completely. As it collapsed and burned, the door created a fire damage pattern just inside the doorway near the floor on the left wall (see Figure 6.108e). This fire damage is distinct from the other damage in the room.

(a) Exp. 3 Bedroom 3

(b) BR 3 Head of the bed wall

(c) BR 3 Window wall

(d) BR 3 Wall dresser wall

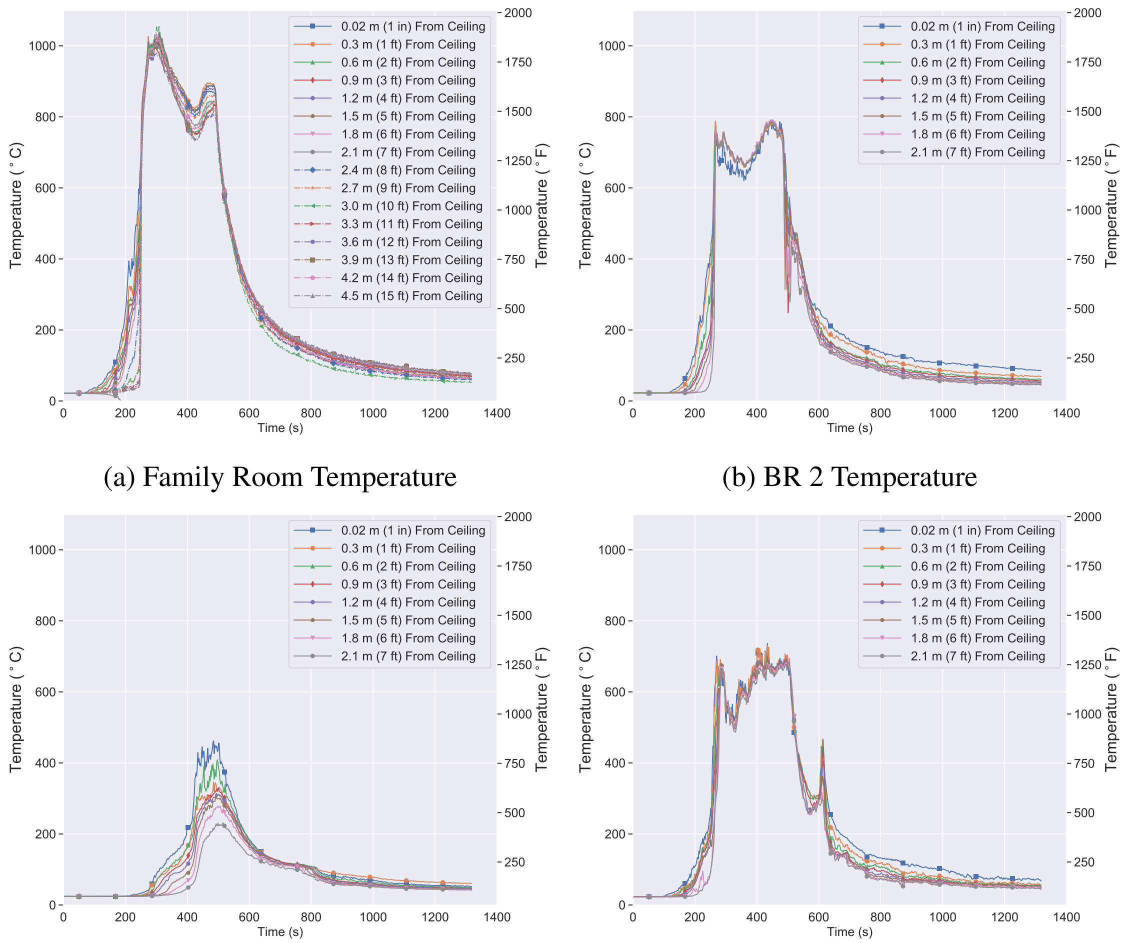
(e) BR3 Entry door wall

(f) BR3 Floor

Figure 6.108: Experiment 3, bedroom 3 post-experiment photographs.

In Experiment 4, bedrooms 2 and 4 had open doors and open windows. Bedroom 3 had a closed hollow-core door and a closed exterior window. Bedroom 3 was located on the hallway next to bedroom 4 on the front side of the structure. Bedroom 2 was located on the back side of the structure. Further, bedroom 2 had a smaller window, which would restrict the hot gas exhaust flow more than the window in bedroom 4.

Figure 6.109 shows the temperature comparisons of the family room and bedroom 2, 3, and 4. Both bedroom 2 and 4 reached flashover conditions. Based on temperatures, bedroom 4 was burning more efficiently than bedroom 2. Flames were observed exiting the window of bedroom 4 shortly after flashover. The flow out of the bedroom 2 window was black smoke changing to flames just prior to suppression. The delay of heat entering bedroom 3 appears in Figure 6.109c. Based on the temperature increase in bedroom 3, the hollow-core wood door heldup to post-flashover exposures for at least 2 min.



(a) Family Room Temperature

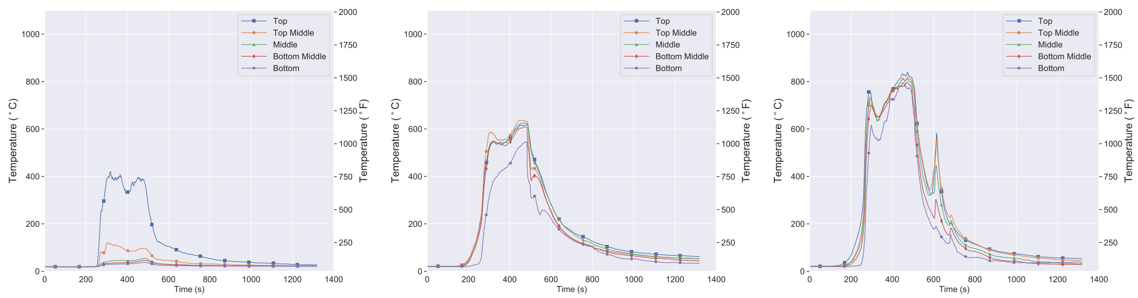
(b) BR 2 Temperature

(c) BR 3 Temperature

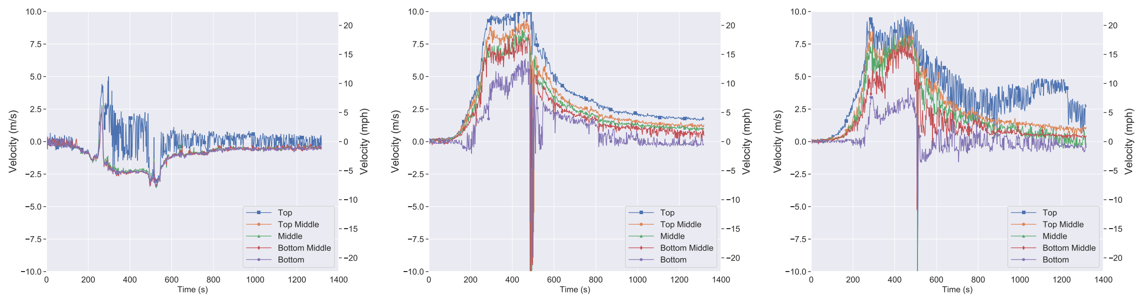
(d) BR 4 Temperature

Figure 6.109: Experiment 4, Family room, Bedroom 2, 3 and 4 temperature comparison.

Figure 6.110 compares the temperatures and velocities in the three open exterior vents. During the period that the fire was growing and then transitioning to flashover, the front door was a unidirectional intake vent. A similar flow behavior was seen in Experiment 3 but it did not last as long as the total inflow in this experiment, which was approximately 100 s. The flow in the front doorway then changed to full exhaust before settling into a bidirectional flow. Three-quarters of the front door acted as an air intake vent during most of the post-flashover burning period. Both windows exhibited unidirectional exhaust flow post-flashover. The large negative velocity data spikes were caused by suppression water impacting the velocity probes.



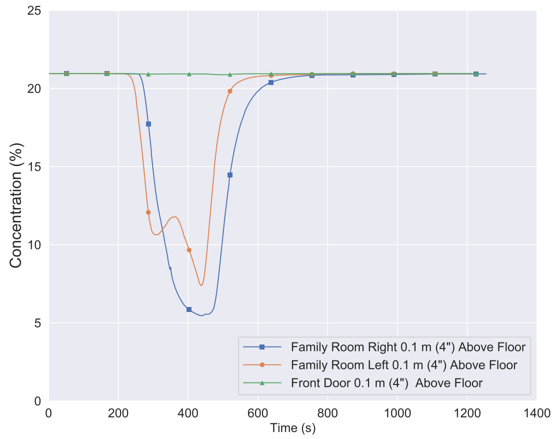
(a) Front Door Temperature (b) BR 2 Window Temperature (c) BR 4 Window Temperature



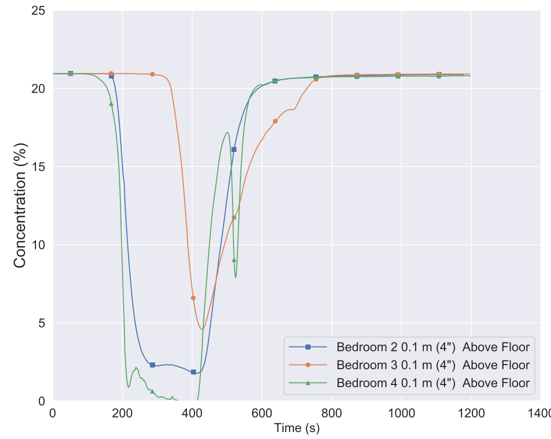
(d) Front Door Velocity (e) BR 2 Window Velocity (f) BR 4 Window Velocity

Figure 6.110: Experiment 4, front door, bedroom 2 and 4 window comparison.

Oxygen probes were positioned 0.1 m (4 in) above the floor, below the windows in bedroom 2, 3, and 4. The oxygen measurements from the three bedroom are compared with oxygen concentrations measured near the floor in the family room and near the front door in Figure 6.111. The open bedrooms had the lowest readings. Bedroom 4 had the most flaming combustion and oxygen concentration readings near zero. Bedroom 2 also had flaming combustion on the interior but appeared to be fuel rich, based on the black smoke exiting the window. Once the door to bedroom 3 failed, the oxygen concentration decreased to 5%, but there was no active burning in that room.



(a) Front Door and Family Room



(b) BR 2, 3, and 4

Figure 6.111: Experiment 4, front door, family room, and Bedroom 2, 3, and 4 oxygen comparison at 0.1 m above the floor.

On the lower level, the sampling point near the open front door was reading over 20% oxygen, while the probes in the back portion of the structure in the family room reached lows between 5% and 10%. Keep in mind that flaming combustion continued in the family room for the duration of the experiment. The oxygen sampling position on the left side of the family room near the TV stand had higher oxygen values throughout most of the burn. This sampling location was the closest to the front door.

Figure 6.112 shows photographs of fire damage inside bedrooms 2, 3, and 4. Bedrooms 2 and 4 had fire damage from the ceiling down to the floor that was consistent with a post flashover fire environment. Bedroom 4 had the most gypsum wallboard area that was clean burned. Bedroom 2 had more soot on the ceiling and walls than bedroom 4. Bedroom 3 had thermal damage to plastic material in the lamp shade, and the burned door. The only other damage in bedroom 3 was a coating of soot on all of the surfaces.

(a) Bedroom 2

(b) Bedroom 3

(c) Bedroom 4

Figure 6.112: Experiment 4, bedroom 2, 3, and 4 post-experiment photographs.

Figure 6.113 shows the doorways of the three bedrooms. The doors to bedrooms 2 and 4 had burned away completely. In each case, the combustion of the door against the wall (right of each doorway in the photographs) generated a distinct pattern. The remains of the door to the bedroom may have collapsed post-suppression because there were no burn marks in the carpeting.

(a) BR 2 Door (b) BR 3 Door (c) BR 4 Door

Figure 6.113: Experiment 4, Bedroom 2, 3, and 4 door post-experiment photographs.

6.3 Application to NFPA 921

In this section relevant portions of NFPA 921 [4] were identified as being supported with the results from these experiments. In many cases, the current information in the guide was based on a fire in a single compartment. This study expanded on the single compartment premise with the experiments taking place within residential scale structures. The portions of NFPA 921 identified include: compartment fire phenomena, from “Chapter 5 Basic Fire Science”, fire effects and patterns from “Chapter 6 Fire Patterns”, and several types of analysis methods from “Chapter 18, Origin Determination”.

6.3.1 Compartment Fire Phenomena

The data and videos from each of the structure fire experiments provide examples of the stages of fire development. In the experiments without an open vent to the exterior, oxygen depleted decay occurred.

Each of the experiments exhibited a fire plume, ceiling jet, and hot gas layer development. In the experiments with adequate ventilation, flashover occurred. In the experiments with no open exterior vents or intake air vents remote from the room of origin, the fire growth and development was impacted.

6.3.2 Fire Patterns

Many of the fire effects identified in NFPA 921 were generated during the structure fire experiments. These fire effects included: deposition of smoke on surfaces, calcination, clean burn, and distorted light bulbs. Fire patterns, as noted in NFPA 921, are visible or measurable physical changes or identifiable shapes formed by a fire effect or a group of fire effects included: lines of demarcation, plume generated patterns, ventilation generated patterns, effects of room ventilation on pattern magnitude and location, hot-gas layer generated patterns, heat shadowing, protected areas, pattern geometry, flashover and full room involvement, and the combination of patterns.

6.3.3 Origin Determination

As applied to these experiments, the focus was to determine the part of a structure where the point of origin of a fire was reasonably believed to be located. Several methods could be examined based on the data in this report: sequential pattern analysis, consideration of all patterns, and fire dynamics specifically with regard to the availability of oxygen.

7 Future Research Needs

This research project addressed a limited number of geometry, fuel, and ventilation configurations. Decisions were made during the design of the experiments to eliminate a number of variables in order to develop a foundation of data that could be used to show cause-and-effect relationships regarding the impact of ventilation in the selected scenarios. This data can be used for additional analysis and future research. However, many questions about the generation of fire patterns were not within the design of this study, and during the course of the study additional questions were raised.

7.1 Construction Methods

In these experiments, the interior of the structures had two layers of gypsum board installed on the ceilings and walls. There were two reasons for doing this: 1) to maintain the pattern on the interior surface of the wall or ceiling by providing additional mass behind the 12.7 mm (0.5 in) lightweight gypsum board in an effort to keep it in place, and 2) to maintain the structural integrity of the test structures in order to complete the planned series of experiments.

Future research could use a similar full scale structure fire experiments constructed with a single layer of the lightweight gypsum board that has evolved into the de facto standard for residential construction and repair. In addition, conduct comparative experiments with the 30% heavier gypsum board that lightweight material replaced. Interesting benchmarks could include how long the materials remained in place post-flashover, how the change in materials impacted calcination and depth probe measurements. Bench-scale testing was conducted on one type of lightweight gypsum board by Wolfe and Gottuck. When conducting depth probe measurements, they determined that the lightweight gypsum wallboard needed a lesser amount of force to penetrate relative to the traditional wallboard [39].

7.2 Ventilation Timing

Typically the ventilation configuration was static during these experiments. In other words, the experiments were designed to have a fixed ventilation condition such as a closed or open door throughout the duration of the experiments as a way to determine the repeatability of the fire dynamics within the structures.

An examination of the impact on fire growth and the resulting damage of the opening of doors and or windows during the course of the fire development would be useful to understand. A next step would be to correlate window failures to fire growth and the subsequent response. Another point of interest would be the impact of fire department ventilation such as opening doors, venting windows, making vertical vents and positive pressure attack. All have the potential to change the flow paths, fire growth, and resulting fire damage patterns.

7.3 Mechanical Ventilation

What is the impact of ventilation supplied by a heating, ventilation, and air conditioning (HVAC) system in a fire building? Does the system support combustion by moving air from remote parts of the structure to the fire area? Does the ventilation generate fire patterns remote from the area of origin in a closed structure? Does the smoke from a growing room and contents fire overcome the ventilation system and compromise its ability to move air due to a blocked filter or thermal damage to the fan unit?

7.4 Vertical Fire Flows

When conducting a fire experiment in a single room with an open door, the flow of smoke and air at the doorway is predictable, assuming no wind effects. As the fire grows, the hot gases start to flow out of the doorway. The neutral plane is established as the boundary between the higher-than-ambient-pressure hot gases leaving the room and the lower-than-ambient-pressure gases, which allow ambient-pressure gases to enter the room. In other words the open doorway serves as a bidirectional vent.

During some of the family room fires in the two story structure, this typical progression was not followed. In some cases, due to rapid fire growth in the two story family room the smoke was forced out of the open front doorway, using the entirety of the open doorway as a unidirectional exhaust vent. Then conditions would change and the door would serve as a bidirectional vent. In other family room fire experiments where bedroom windows on the upper level were opened, there were periods of time during the fire growth stage that the open front doorway acted as a unidirectional intake vent. Later in the fire. the front door became a bidirectional vent. If the fires were suppressed at those times when the doorway was acting as a unidirectional vent, what would the fire damage patterns be?

Whether the fire occurs in a 100-year old brownstone or triple-decker, or in a one-year old four-story town home there is potential for non-typical fire spread and the resulting non-typical fire damage patterns. How would vents below or above the fire floor impact the fire damage patterns?

7.5 Gas Concentration Measurements

Qualitatively applying the concept of the fire triangle to analyzing where pre-flashover and post-flashover fire damage can occur as a means for locating the area of origin has been documented by Cox and a team from ATF in their Origin Matrix paper [24]. In a structure that has a fuel load distributed throughout, such as a furnished residence, the analysis tends to focus on where could the oxygen supply be at a given time in the fire.

This study showed in many cases that as oxygen concentration decreased to 15% or below, flaming combustion in that area decreased or stopped altogether. There were also instances where the measured oxygen concentration was near 0% because flaming combustion was local to the sampling point. Eight oxygen meters were used in these experiments, installed around the fire origin or along the flow path between the fire and the exterior vent. The sampling points were at different elevations as well.

That said, additional efforts must made to improve the understanding of the oxygen concentration and the interaction of combustion products post-flashover with regard to the fire's ability to generate damage patterns.

8 Summary

Underwriters Laboratories Inc. Firefighter Safety Research Institute (UL FSRI) conducted a study to examine how ventilation impacts fire damage patterns in single family homes. The test structures included a traditional 111 m^2 (1200 ft^2) single story ranch style structure and a 297 m^2 (3200 ft^2) two story colonial style structure. The two story colonial had a contemporary open floor plan design with a two-story family room and open foyer. The experiments were planned with the assistance of a technical panel that included members of ATF, IAAI, NAFI, NASFM, NIST, NIST OSAC, and NFPA 921.

The full-scale scenarios ranged from fires in the structures with no exterior ventilation to room fires with flow paths that connected the fires with remote intake and exhaust vents. In the single story structure, two replicate fires were conducted for each room of origin and each ventilation condition. Rooms of fire origin included the living room, bedroom, and kitchen. In the two story structure, the focus was on varying the flow paths to examine the change in fire behavior and the resulting damage. Family room fires were conducted with five different ventilation configurations. In addition, two experiments were conducted in small rooms in the two story. The laundry room fire had a remote exterior vent, and the den fire had a vent adjacent to the fire as well as a remote vent. In the exterior vent experiments, the baseline vent was an open front door. Any additional vents were windows. After each fire scene was photographed, the interior finish and furnishings were replaced in affected areas of the structure to prepare for the next experiment.

Instrumentation was installed to measure gas temperature, gas pressure, and gas movement within the structures. In addition, oxygen sensors were installed to determine when a sufficient level of oxygen was available for flaming combustion. Standard video and firefighting thermal imaging cameras were also installed inside of the structures to capture information about the fire dynamics of the experiments. Video cameras were also positioned outside of the structures to monitor the flow of smoke, flames, and air at the exterior vents. Although the number of data channels used varied based on the ventilation configuration, the single story had 140 instruments installed, and the two story had 195 instruments installed. During the experiments, each channel was scanned every second and recorded on a computerized data acquisition system.

Each of the fires were started from a repeatable, small flaming source. The fires were allowed to develop until they self-extinguished due to a lack of oxygen or until the fire had transitioned through flashover. The times that each fire burned post-flashover varied from less than 1 min in experiments where the fire self-extinguished due to a lack of oxygen, to 7 minutes where the fire could sustain post-flashover burning. The goal was to have patterns remaining on the ceiling, walls, and floors post-test. In total, 13 experiments were conducted in the single story structure and eight experiments were conducted in the two story structure. All of the experiments were conducted at UL's Large Fire Laboratory in Northbrook, IL.

After the experiments, the fire scenes were documented, the data was plotted, and the videos were reviewed. The numerical and visual field data were compared between the experiments to examine the repeatability of replicate fire experiments, and to examine the correlation of the change in fire damage relative to the change in ventilation. One of the fundamental concepts demonstrated by these experiments is the relationship between oxygen consumption and the generation of heat.

A review of the results from the 21 full-scale fire experiments yielded the following:

1. Increasing the ventilation available to the fire resulted in additional burn time, additional fire growth, and a larger area of fire damage within the structures. These changes are consistent with fire dynamics based assessments and were repeatable.

2. Fire patterns within the room of fire origin led to the area of origin when the ventilation of the structure was considered.

3. Fire patterns generated pre-flashover persisted post-flashover if the ventilation points were remote from the area of origin. Pre-flashover fire damage patterns near open exterior vents were more difficult to distinguish from post-flashover damage, or were eliminated completely.

4. The location of the ventilation relative to the origin of the fire changed the location and extent of the fire damage within the structures as the ventilation configuration affected the availability of the oxygen to the fire.

The report, the time histories of the data, and the videos from this study provide foundational documentation for the understanding of ventilation-controlled fires and the resulting fire patterns. This study supports the understanding that separate and distinct fire patterns can be generated during different stages of the fire and by ventilation-controlled burning conditions in a structure.

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