Analysis of the Coordination of Suppression and Ventilation in Multi-Family Dwellings

Keith Stakes
Julie Bryant
Nicholas Dow
Jack Regan
Craig Weinschenk

UL Firefighter Safety Research Institute
Columbia, MD 21045

This publication is available free of charge from:
https://dx.doi.org/10.54206/102376/YMPJ4047

UNDERWRITERS LABORATORIES™

Analysis of the Coordination of Suppression and Ventilation in Multi-Family Dwellings

Keith Stakes
Julie Bryant
Nicholas Dow
Jack Regan
Craig Weinschenk

UL Firefighter Safety Research Institute
Columbia, MD 21045

June 23, 2020

This publication is available free of charge from:
https://dx.doi.org/10.54206/102376/YMPJ4047

UNDERWRITERS LABORATORIES™

Acknowledgments

This project was funded through a grant from the Department of Homeland Security (DHS) Federal Emergency Management Agency's (FEMA) Assistance to Firefighters Grant (AFG) Program under the Fire Prevention and Safety Grants: Research and Development (EMW-2015-FP-00361). This critical fire service research project would not be possible without this funding and continued support.

A research project of this magnitude is only accomplished through the extraordinary efforts of the many project partners and team members. First and foremost, the authors thank the men and women of the Cobb County Fire and Emergency Services Department. Their tireless effort, professionalism, and hospitality were integral in the conduction of these acquired structure burns. From initial contact regarding the availability of these structures to the final breakdown of all instrumentation, they were excellent partners in conducting full-scale fire research for the fire service. Similarly, the authors also thank the Atlanta Fire Rescue Department for their support with additional staffing, apparatus, and equipment. A special thank you goes to the Cobb County Department of Transportation for the generous donation of the structures utilized in these experiments.

The authors thank the members of the project's fire service technical panel, listed in the accompanying table, for providing support during the development and planning phase of this project and for contributing valuable feedback regarding the project results and conclusions.

Coordinated Fire Attack Technical Panel

Name	Department
Christopher Byrne	Colorado Springs Fire Department
Tony Carroll	District of Columbia Fire and EMS Department
Chad Christensen	Los Angeles County Fire Department
Shea Chwialkowski	Richfield Fire Department
Danny Doyle	Pittsburgh Fire Department
Brad French	Dayton Fire Department
Russell Gardner	Sacramento Metropolitan Fire Department
Scott Gray	Seattle Fire Department
David Guercio	Baltimore City Fire Department
Greg Hubbard	Orange County Fire Rescue
Curt Isakson	Escambia County Fire Rescue
Cody Johnson	Homer Volunteer Fire Department
Frank Leeb	Fire Department of New York
Dennis LeGear	Oakland Fire Department
Stephan Lopez	Dallas Fire-Rescue
Ray McCormack	Fire Department of New York
James Mendoza	San Jose Fire Department
Nicholas Papa	City of New Britain Fire Department
Joe Pronesti	Elyria Fire Department
Richard Riley	Kentland Volunteer Fire Department
Andrew Ruiz	Los Angeles Fire Department
Terrence Sheppard	Chicago Fire Department
Eric Staggs	City of Spokane Fire Department
Chris Stewart	Phoenix Fire Department

Finally, the authors would also like to commend the commitment and dedication of the entire UL FSRI team who impacted this project from planning through completion. A special thank you to Jennifer Williams, Sarah Huffman, Josh Crandall, Steven Robert and Patrick Havey for their efforts in logistics and marketing to help make this project impactful to the fire service. The support of Dan Madrzykowski, Gavin Horn and Stephen Kerber with their technical input and reviews throughout the various project stages has been invaluable. An additional thank you to Roy McLane of Thermal Fabrication LLC for his tireless support in both the planning and execution of the experiments.

Contents

List of Figures

List of Tables

List of Abbreviations

AFG	Assistance to Firefighters Grant program
CO	Carbon monoxide
CO_2	Carbon dioxide
DHS	Department of Homeland Security
FED	Fractional effective dose
FEMA	Federal Emergency Management Agency
HRR	Heat release rate
FER	Rate of change of fraction effective dose
IR	Infrared
O_2	Oxygen
PPA	Positive pressure attack
PPV	Positive pressure ventilation
TIC	Thermal imaging camera
UL FSRI	UL Firefighter Safety Research Institute

Abstract

The majority of the existing full-scale fire service research studied the impact of tactics on the residential fireground, specifically in single-family structures. This study builds upon prior research by conducting thirteen experiments in three-story, multi-family dwellings to quantify the impact of coordination between ventilation and suppression actions. Experiments were conducted in four, garden-style apartment buildings; each of which had two lower-level units, four first-floor units, and four second-floor units. The apartments shared a common stairwell that was enclosed for all of the experiments in this study.

To examine the effectiveness of tactics in the fire apartment, common stairwell and applicable exposure apartments, four experiments were conducted in lower-level apartments, seven were conducted in first-floor apartments, and two were conducted in second-floor apartments including both bedroom and kitchen/living room fires. The fire size varied based on the amount of initial ventilation provided. The main control variables included the location of initial water application, the ventilation method, and the timing of ventilation relative to water application. The suppression tactics included interior water application, exterior water application followed by interior water application, and a combined interior and exterior water application. The ventilation tactics examined in these experiments included horizontal, vertical, positive pressure, and hydraulic ventilation.

Similar to previous experiments in acquired single-family structures, there was no meaningful increase in temperature outside of fire rooms when ventilation tactics were executed in close coordination with (shortly after or shortly before) the onset of suppression. In contrast, for experiments where ventilation occurred with delayed suppression, temperature exposures increased throughout the fire apartment, and in experiments where the apartment door was left open, temperatures and carbon monoxide exposures increased throughout the common stairwell.

Suppression actions, whether interior or exterior, resulted in a decrease in temperatures and gas concentrations at locations where occupants may potentially be located. The enclosed common stairwell, a unique feature of this experimental series, acted as capture of combustion products. Opening the apartment door to gain access should be thought of as an important ventilation action, both in terms of its potential to cause fire growth and its potential for smoke movement into the stairwell, limiting the egress for potentially trapped occupants in exposure units. Tactics such as door control, positive pressure ventilation, and hydraulic ventilation which were used both simultaneous with and sequentially post-suppression were shown to limit gas flows into the stairwell. After effective suppression, structure ventilation operations should similarly be cognizant of gas flows, with the aim of establishing flow throughout all areas where occupants may be located.

1 Introduction

The purpose of this study is to improve fire service knowledge of fire dynamics and the impact of their tactics through a better understanding of how suppression and ventilation are coordinated on the fireground in multi-family residential structures. This project expands upon previous research led by the UL Firefighter Safety Research Institute (FSRI) that examined the impact of various fire service tactics on fire behavior in single-family dwellings [1–9]. Those experiments were conducted in both purpose-built structures and acquired structures, and investigated the impact of tactics independent from one another. These experiments in acquired multi-family residential structures are one part of a three-part series titled the *Study of Coordinated Fire Attack Utilizing Acquired Structures*. The other two parts of the project examined single-family dwellings and an exploratory examination of ventilation in commercial (strip mall) fires. The intent of studying fires in multi-family dwellings, specifically garden-style apartments, was to determine the applicability of previous research findings in a different structure with different hazards.

Every fire control strategy requires coordination regardless of staffing, rural or urban location, career or volunteer coverage, and overall response model to structure fires. Understanding what makes coordination successful or not is of utmost importance to the entire fire service. Successful coordination maximizes the ability to achieve the fire service priorities of life safety, property protection, and environmental conservation. As the fire environment continues to evolve, fire departments adapt strategies and tactics. These operational changes require a solid understanding of the impact of various suppression and ventilation operations on firefighter safety and occupant survivability. However, fire departments may lack the ability to define what constitutes a successful coordinated fire attack and to provide their members with the tools to think critically and make decisions based on the fireground conditions encountered.

Many variables can impact coordination on the fireground and ultimately the resulting fire dynamics inside the structure. Timing is a key component that must be understood if tactics are going to be executed in coordination. A tactic such as horizontal ventilation can be very effective in certain areas of a structure at a certain time. However, in certain instances, horizontal ventilation may only be effective if coordinated with suppression. Data is needed to understand the science of coordination and how tactics link together to lead to the most effective fire control strategy and most positive outcome for occupant survivability and firefighter safety.

Using acquired structures, these experiments were designed to bring the laboratory to the street. Several different fire scenarios were tested, including below-grade, at-grade, and above-grade fires with varying ventilation configurations and levels of fire showing on arrival. The tactics studied included horizontal, hydraulic, and positive pressure ventilation combined with interior or exterior/interior suppression methods. Measurements were taken of gas temperatures, gas flow velocities, differential pressure, and gas concentrations throughout the structure along with standard and infrared (IR) video of the experiments. Fuel loads were representative of furnishings found in structures across the country. Fuels were consistent across this experimental series so the variations in coordinated suppression methods could be compared.

Multi-family dwellings are commonly defined as separate residences of two or more families, but that broad definition does not clarify the type of structure in which these residences occupy. The experiments in this study were conducted in multi-family, garden-style apartment buildings that were slated for demolition. A garden-style apartment building is typically two to three stories in height and can be as tall as six stories with the primary entrance to each unit off a common stairwell. That stairwell may or may not be enclosed. The stairwells in this experiments were purposefully enclosed to capture data about the impact of potential smoke transport assuming a worst case scenario when compared to an open breezeway.

It is important to remember that while there may be similarities, the acquired garden-style apartments buildings used in these experiments do not represent all multi-family structures. Additionally, each apartment in this series featured the same layout with the exception of the second-floor living room ceiling height. The square footage, compartment sizes, wall configurations, and other construction features within each unit were fixed. The hazards present and conclusions found as a result of this study may not uniformly translate across other types of multi-family dwellings.

This study utilized ventilation and suppression methods that were decided prior to each experiment based on discussions with the project technical panel. The ventilation and suppression crews for these experiments were walked through the structure and were familiar with the layout and fire location prior to the start of each experiment. Each crew was adequately staffed. The equipment utilized during the experiments was pre-deployed and checked, and the water flow rate and pressure of each hoseline were set prior to ignition.

The type, timing, coordination, and execution of fireground tactics were carefully controlled to maximize connections between prior research projects and new insights into the coordination of ventilation and suppression methods over the 13 experiments conducted for this series.

1.1 NIOSH Firefighter Fatality Investigations

The National Institute of Occupational Health (NIOSH) investigates firefighter line of duty deaths (LODDs) under the Fire Fighter Fatality Investigation Program. Several firefighter fatality investigation reports published by NIOSH indicate uncoordinated suppression and ventilation tactics affected the outcome at each incident [10–15]. Discussion and recommendations by NIOSH state that suppression and ventilation operations should be coordinated, but the manner in which these tactics are coordinated are not addressed. Several NIOSH LODD reports highlight the need for further research into fire service strategy and tactics in multi-family dwellings.

In 2001, a career firefighter was severely burned while operating inside a two-story commercial/residential structure in New Jersey. The victim was operating as a member of a two-person search team. The victim's low-air alarm activated and he informed his partner. The partner assumed the victim was exiting the structure, but he continued to search. Simultaneously, other crews were deploying a hoseline up the stairs and laddering the exterior. The incident commander believed the hoseline was in position and called for the apartment windows to be ventilated. The ventilation provided air to an under-ventilated fire which led to an increase in the heat release rate of the fire. Conditions rapidly deteriorated, driving the victim to dive out of a second-story window as the apartment flashed over. The New Jersey Division of Fire Safety (NJDFS) report states that "regular communication between interior, exterior, and command personnel is key to coordinating fireground operations between search, ventilation, and suppression personnel [10]."

In 2011, a fire in a garden-style apartment in Baltimore County, MD, resulted in the death of a firefighter who was searching for reported trapped occupants. The victim was searching a third floor apartment, two floors above the fire origin on the first floor (terrace level). Other crews were simultaneously commencing fire attack in the common stairwell and searching for and removing occupants on the second floor. Fire extended out the side C sliding glass door in the fire apartment and extended up the rear of the building, igniting the combustible balcony on the second floor. The exterior fire caused the sliding glass door into the apartment to fail, igniting the apartment's contents. Conditions on the second floor, in the common stairwell, and on the floor above the firefighter's location deteriorated rapidly as this new flow path was established and fire spread throughout. This was compounded as the doorway from the apartment to the stairwell was held open. The common stairwell was engulfed in fire and no longer served as an egress path for the crew operating above. One firefighter was able to make it to a window and bail out, sustaining serious injury. The other firefighter was unable to locate an exit, and he succumbed to his injuries. The NIOSH report states, "In this incident, crews were making uncoordinated attacks simultaneously from side A and side C of the structure...Crews arrived and went to work on suppression and search activities without direction or coordination of the other crews...It is very important to coordinate ventilation with interior attack crews and the Incident Commander. Without this coordination effort, the process becomes ineffective and can compromise firefighter safety [11]."

In 2012, a career captain in Illinois succumbed to injuries sustained at a 2.5 story apartment building fire. Two of the contributing factors cited by NIOSH were "horizontal ventilation contributed to the rapid fire growth" and "fireground communications." One of NIOSH's key recommendations was to "ensure that fireground operations are coordinated with consideration given to the effects of horizontal ventilation on ventilation-limited fires." In this incident, an exterior rear door was opened while the victim and crew were inside the structure. The ventilation-limited fire then received an influx of fresh air, which caused the fire to grow and the failure of a closed door to the second floor. This closed door was the only separation between the fire and the victim's crew. Suppression and horizontal ventilation were not coordinated or communicated with one another, and this was a cited as a contributing factor [12].

In 2014, two career Ohio firefighters died in a second-floor apartment fire when a combination of wind and uncoordinated ventilation caused rapid fire growth. Without a proper 360-degree size-up, the full extent and hazards associated with the fire were not realized, including an open second-floor door on side D. It was determined the best access to the second-floor apartment was through a window on side A. The attack crew entered the apartment with an uncharged hoseline and were overcome by intense heat and smoke. The uncoordinated ventilation of the side A second-floor apartment window, side A first-floor garage door, and side D first-floor apartment door established two wind-driven flow paths in the structure, increasing the size and severity of the first-floor garage fire. Two NIOSH recommendations were to "ensure that the incident commander conducts an initial 360-degree size-up and risk assessment of the incident scene" and to "ensure all fireground ventilation is coordinated with firefighting operations [13]."

Also in 2014, a multi-family brownstone fire resulted in the death of two career firefighters in Massachusetts. A lieutenant and a firefighter stretched an uncharged hoseline through the front door and into the basement. A rear basement door was left open by a maintenance worker investigating a smoke alarm activation, while the front doors were left open by an escaping occupant. High winds coupled with the uncontrolled flow path rapidly deteriorated fire conditions, trapping the lieutenant and firefighter in the basement. Water was supplied by the attack engine, but high heat burned through the hoseline on the stairs. Although high winds contributed to the rapid fire progression, NIOSH suggested firefighters should "understand the influence of ventilation on fire behavior and effectively apply ventilation and fire control tactics in a coordinated manner [14]."

In 2017, a career firefighter in Connecticut died during a low-air emergency in a multi-family dwelling fire. Uncoordinated ventilation caused rapid fire growth in a second-floor apartment. During interior firefighting operations, multiple crews were operating to suppress flames, check for extension, and ventilate the structure. Uncoordinated ventilation of a second-floor window resulted in a near immediate increase in temperature as the ventilation-limited fire entrained fresh air. Conditions in the structure became untenable and crews retreated out of the structure. Although the firefighter fatality was not a direct result of the uncoordinated ventilation, NIOSH recommended that "fire departments should integrate current fire behavior research findings ... into operation procedures" because ventilation was conducted in an untimely and uncoordinated manner during this incident [15].

1.2 Fire Service Publications

Fire service publications and training manuals were reviewed with respect to multi-family structures. The publications discussed here represent a subset of those documents with a focus on those that discussed hazards associated with garden-style apartments and how departments respond to and overcome those challenges.

Garden-style apartments are typically characterized by construction features such as stacked interior floor plans with potentially unprotected utility shafts or pipe chases, shared entrance hallways, common roof structures, and lightweight construction. These buildings are typically connected to create an apartment complex and are built to complement the environment they are in (i.e., the building may have two above-grade units on side A and three above-grade units on side C), which limits fire department access to the buildings themselves as well as municipal water supplies [16]. Additional considerations include positioning apparatus to establish water supply and avoid bottlenecking, bundle- or leader-line hose deployments, and the importance of pre-planning a complex.

A 2010 article in *Fire Engineering* summarized a third-floor apartment fire and the actions the crew took to coordinate both ventilation and suppression [17]. Ciampo began by summarizing key building features he observed to assess the hazards presented by the structure. Tasked with checking for fire extension in the attic, he led his crew into the structure where small inspection holes were made in each room of the exposure apartments, confirming the fire had not surpassed their location. Ciampo and his crew then pre-punched large openings in the ceiling but ensured they were not opened until the hoseline assigned to accompany his crew was in position and ready to operate. The coordination of suppression and ventilation along with situational awareness ensured knock down of the apartment fire without incident [17].

In a 2007 article in *FireRescue1*, an overview of the general objectives during garden-style apartment fires and ways of accomplishing those goals was provided [18]. Bailey summarized the location of each hoseline and the objectives of the respective crews to achieve the first objective of life safety: Keeping the ingress and egress paths (i.e., common shared hallways) clear of smoke. He then described two types of garden-style apartment fires: smoke showing without visible fire and fire venting from a compromised roof. For both situations, Bailey described the suppression tactic employed to suppress the fire. He described using the scuttle hole at the top of the shared hallway to accomplish the second objective of incident stabilization via ventilation.

The need to coordinate tactics for successful fire suppression and ventilation is a recurring theme in fire service training manuals. This consistent theme often lacks detail in the level and type of coordination necessary. In addition to the lack of detail, it's also frequently not clear on whether steps occur in a specific order or simultaneously depending on the manual referenced.

The Essentials of Firefighting, 7th Edition, contains information in several chapters about the need for fireground coordination. In the chapter discussing tactical ventilation, it is stated that ventilation "must be coordinated with fire-suppression operations to prevent unwanted consequences for crews or victims." The definition of tactical ventilation is "the planned, systematic, and coordinated removal of heated air, smoke gases or other airborne contaminants from a structure, replacing them with cooler and/or fresher air to meet the incident priorities of life safety, incident stabilization, and property conservation" which provides little context as to how the coordination is achieved. The chapter further discusses the need for flow path control and the potential for rapid fire development with uncoordinated fire-suppression. In the chapter on fire suppression, a list of fireground considerations includes the need to "always coordinate attack with ventilation [19]." There is little additional information describing the means of coordinating these two tactics, other than conducting early suppression and performing ventilation nearest the fire location. Further details are needed to describe how to best conduct ventilation and suppression operations in coordination on the fireground.

The Fire Engineering Handbook for Firefighter I and II discusses the need for coordinated ventilation and fire attack operations. The Basic Fire Attack chapter indicates that a Chief Officer will direct the ventilation team to "break or take the windows ahead of the hoseline, then direct the hose team to advance to the seat of the fire." There is little additional information providing context as to why the actions need to be coordinated, why the ventilation should precede the suppression operations and in what situations this should apply. In the Ventilation chapter, the explanation of Venting for Fire indicates this type of ventilation "is performed and coordinated in unison with the engine company's advance on the fire [20]." The section goes on to say that venting prematurely or prior to the engine company having water can increase the fire size and intensity. There is discussion throughout the text about the need for coordinated actions but more clarity is needed to determine what type of ventilation is best suited with suppression, including the where and when on the fireground.

The Structural Fire Fighting: Initial Response Strategies and Tactics, 2nd Edition, states that tactical ventilation "must be coordinated with fire-suppression operations to prevent unwanted consequences for crews or victims [21]." The text further states that ventilation may occur before, during, or after fire suppression operations; however, there is no additional detail provided as to how and when this would occur. Further definition is needed to outline scenarios when ventilation would precede suppression, occur simultaneous with suppression or follow suppression.

1.3 Objectives

As part of previous DHS AFG funded projects, UL FSRI has examined horizontal, vertical, and positive pressure ventilation in addition to interior or exterior/interior suppression methods in single-family residential structures [1–8]. UL FSRI also examined the combined impact of coordinating ventilation and suppression in single-family dwellings as part of this project [9]. Similar to the prior experiments (approximately 100), these experiments utilized furnishings that produced realistic fires to examine fire service ventilation and suppression methods in ventilation-limited fire conditions.

Using prior research as a foundation, these experiments were designed to:

- Quantify the impact of the coordinated ventilation and suppression tactics on fire dynamics, firefighter safety and occupant survival on the fireground through scenarios in multi-family residential structures.
- Compare previous research studies that examined residential fire service tactics in single-family homes to a multi-family residential structure.
- Provide data necessary to understand the impact of coordinated suppression and ventilation in the path of egress in multi-family structures (i.e., shared enclosed stairwell).

2 Experimental Setup

The goal of this study was to evaluate the coordination of fire suppression and ventilation tactics for fires in a multi-family residential structure. Previous UL FSRI research on the residential fireground focused on single-family dwellings. This experimental series examines fires in multi-family dwellings to assess the applicability of single-family dwelling tactics. The experiments included bedroom, kitchen, and living room fires in one-bedroom apartment units in a three-story acquired garden apartment building slated for demolition. A series of 13 experiments was developed to evaluate six different fire scenarios grouped by fire location and initial ventilation conditions.

The main variables, based on discussions with the project technical panel, included the position of initial application of water, the ventilation method, and whether that ventilation was performed prior to or after water was applied to the fire compartment. Although several more strategies were discussed, the selected methods were deemed to represent the majority of tactics initial arriving crews could chose from when presented with a fire in a multi-family residential structure. The following sections address these tactics as grouped by the fire scenario. The use of an acquired structure added other variables, such as specific access issues to certain units, individual apartment layout, unit layout within each building, and weather conditions; these variables are also part of actual fire responses.

2.1 Experimental Structures

Four separate buildings at the Arlington Park at Wildwood apartment complex located in Marietta, GA were acquired for use in this project through cooperation with Cobb County Fire and Emergency Services in conjunction with county representatives from Cobb County, GA. The structures were addressed to Kimberly Village Lane and held the building numbers of 1972, 1974, 1978, and 1980. The building layout within the complex is shown in Figure 2.1.

Figure 2.1: The building layout and corresponding addresses for the acquired structures in the Arlington Park at Wildwood complex [22].

Building 1980 was connected to building 1978 and building 1974 was connected to building 1972. Adjacent buildings shared a common roof and were separated by a firewall. Images of sides A and C of an example building are presented in Figure 2.2. Each building had the same layout: 10 apartment units spanning three floors that were connected by a common stairwell. Two units were on the lower-level and four units were on both the first and second floors. Each building was two stories on side A and three stories on side C. Figure 2.3 shows an isometric view of an exploded CAD drawing for an example building.

(a) Side A (b) Side C

Figure 2.2: Images of the exterior of the buildings at the Arlington Park at Wildwood apartment complex utilized in these experiments.

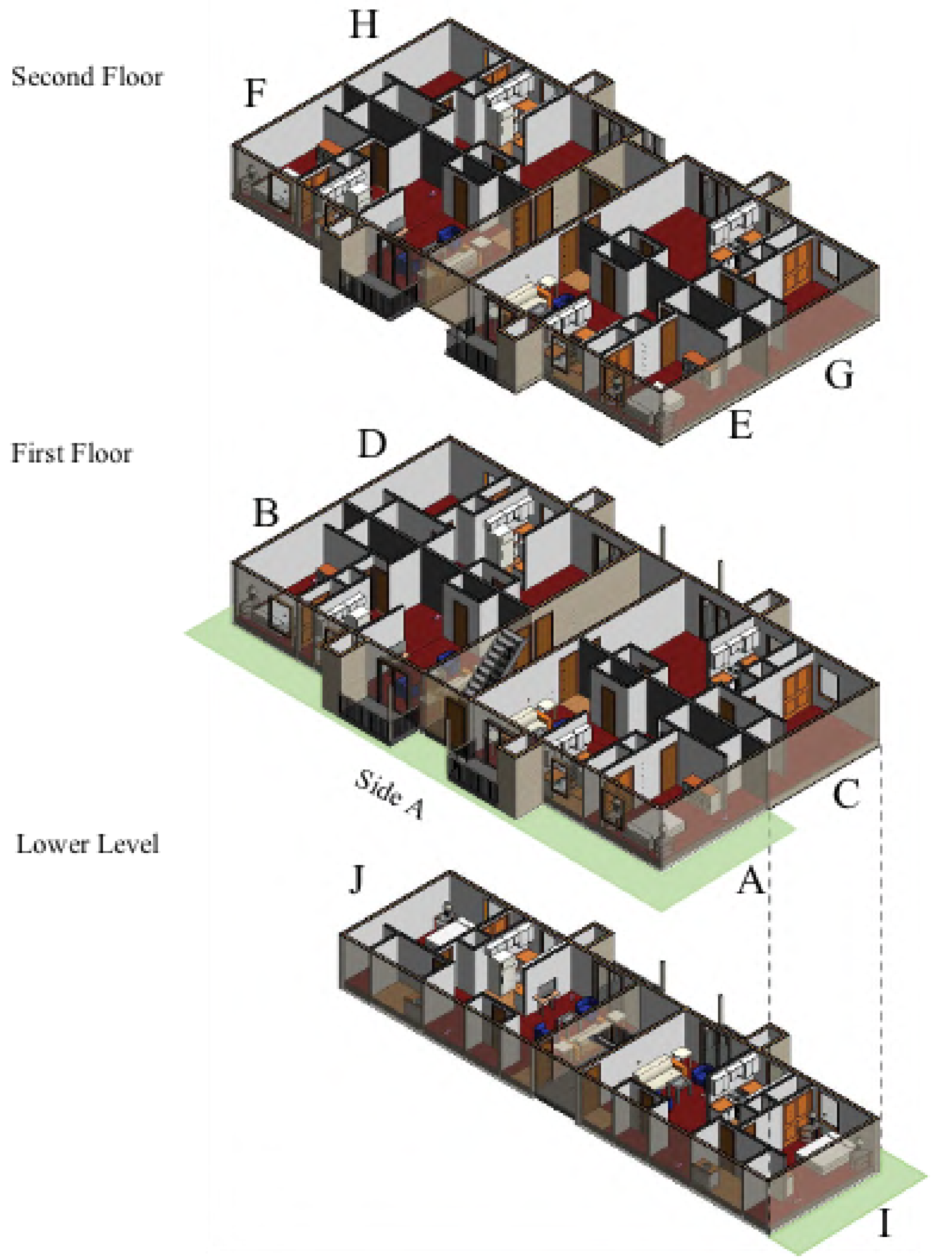


Figure 2.3: An isometric view of each floor from a CAD drawing of a building used in these experiments. The labels A–I indicate each apartment unit.

Each structure was wood-frame, stick-built construction. The construction materials and practices fell within the Type V category incorporating the use of wood as both framing and structural members. There was no wood exposed on the exterior or interior of the structures. The exterior walls of the structures were constructed with standard 2x4 wood stud framing. For exterior walls, the exterior lining included an inner layer of T1-11 plywood siding panels, a vinyl siding outer layer, and the interior lining included 1/2 in. gypsum board and standard grade paint. The interior walls were also constructed with standard 2x4 wood stud framing and lined with 1/2 in. gypsum board on both sides. The only exceptions were the fire-rated walls separating the buildings as well as the apartment units from the stairwell. These walls were lined with 5/8 in. fire-rated gypsum board, and fire caulk was present around all penetrations in the wall. The roof of these structures wooden truss construction incorporating metal gusset plates. The roof deck was comprised of 1/2 in. plywood sheeting topped with tar paper and asphalt shingles. The floor systems in the structures were also of truss construction with metal gusset connections as pictured in Figure 2.4.

Figure 2.4: A view of the underside of the floor construction.

Originally, each stairwell was open to the exterior on sides A and C of the structures, and the walls exposed to the stairwell were lined with an inner layer of T1-11 plywood siding panels and a vinyl siding outer layer, see Figure 2.5a. For the purpose of these experiments, each stairwell needed to be enclosed. Temporary walls were installed on sides A and C of the building to enclose the stairwells as seen in Figure 2.5b. The walls consisted of 2x4 wood stud framing covered by oriented-strand board on the exterior and 5/8 in. fire-rated gypsum board on the interior. A 32 in. wide exterior fiberglass door was installed centered on the temporary side A wall; it served as the only exterior entrance to the stairwell.

(a) Interior of Breezeway, Stairs to Second-Floor (b) Exterior of Breezeway

Figure 2.5: Exterior and interior views of the apartment breezeway, including the constructed wall to enclose the space.

Each apartment unit was 800 sq. ft with one bedroom, one bathroom, a living room, a kitchen, and a balcony (see Figure 2.6). The lower lower and first floor apartments had 8 ft ceilings throughout while the second-floor living rooms had vaulted ceilings that peaked at 11 ft. The bedroom and bathroom were separate compartments with the ability to close a standard interior door and isolate the space if desired. The kitchen, dining room, and living room were connected to one another and are referred to as the common area/space within the apartment. Additionally, each apartment balcony also had an attached utility chase that housed the water heater and additional HVAC equipment. A pipe chase was located just outside the entrance to the bedroom in each apartment and housed the furnace, plumbing, and electrical equipment. Any penetrations between floors had previously installed fire caulk in place.

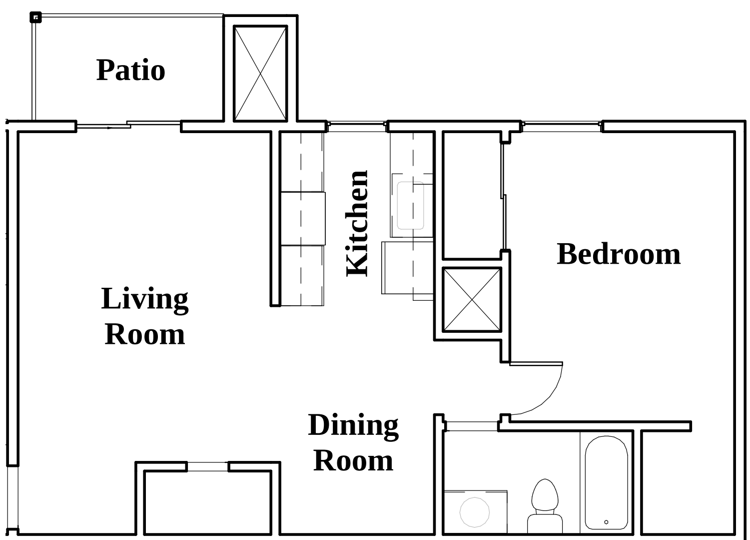


Figure 2.6: A typical apartment layout.

The buildings incorporated individual heating, ventilation, and air conditioning (HVAC) systems for each of the 10 apartment units. Supply vents were located at the ceiling level of the bedroom, bathroom, kitchen, dining room, and living room. A single common return was located near the floor on the base of the heating and cooling unit, located in the pipe chase adjacent to the entryway to the bedroom. For the purpose of these experiments, power to the structures was secured and thus the HVAC systems were not operable. However, the duct network was present and allowed for the movement of fire gases. Additionally, the kitchen range hood was ductless and returned into the space. The bathroom fan was also left in place, which ducted upward through the structure and exhausted out of the roof.

Apartments A and B (on the first floor) and Apartments I and J (on the lower level) were located at grade and had a concrete slab floor. Carpet and padding was installed directly on top of the slab without a wood sub-floor present. Other apartments in the structure (C, D, E, F, G, and H) were elevated and had a 3/4 in. wood sub-floor beneath the carpet and padding.

Table 2.1 shows the experiment numbers, corresponding building, apartment number, floor, and ignition location.

Table 2.1: Experiment Locations

Exp #	Building	Ignition Location		
		Apartment	Floor	Room
1A	1980	I	Lower-Level	Bedroom
1B	1980	J	Lower-Level	Bedroom
1C	1980	B	First-Floor	Bedroom
1D	1980	A	First-Floor	Bedroom
1E	1978	A	First-Floor	Bedroom
2A	1978	B	First-Floor	Bedroom
2B	1978	A	First-Floor	Bedroom
3A	1974	A	First-Floor	Kitchen
3B	1974	B	First-Floor	Kitchen
4A	1980	E	Second-Floor	Kitchen
4B	1980	F	Second-Floor	Kitchen
5	1972	J	Lower-Level	Living Room
6	1972	I	Lower-Level	Living Room

2.2 Experimental Scenarios

The experiments were grouped into six different fire scenarios based on fire location and initial ventilation conditions. Different suppression and ventilation tactics were employed for each experiment to allow comparisons on their relative effectiveness for each scenario. Ventilation tactics included door control, hydraulic ventilation, positive pressure ventilation, and positive pressure attack. Details on each scenario are provided below, and are summarized in Table 2.2.

Table 2.2: Summary of Fire Scenarios

Scenario	Exp. #	Ignition Location	Description
1	1A–1E	Lower-Level/First-Floor Bedroom	Varied Ventilation Tactics with No Fire Showing
2	2A, 2B	First-Floor Bedroom	PPA vs. PPV with Door Control
3	3A, 3B	First-Floor Kitchen	Interior vs. Exterior + Interior Suppression
4	4A, 4B	Second-Floor Kitchen	Interior vs. Exterior + Interior Suppression
5	5	Lower-Level Living Room	Interior Fire Spread
6	6	Lower-Level Living Room	Exterior Fire Spread

2.2.1 Scenario 1: Lower-Level/First-Floor Bedroom Fires, Nothing Showing

Scenario 1 was defined as the interior suppression of a lower-level or first-floor bedroom fire with no fire showing to the exterior. Prior to ignition, all exterior windows and doors were closed. Firefighter intervention began after the fire became ventilation-limited. The ventilation tactic was varied to evaluate the different options for removing smoke from the structure.

Experiments 1A and 1B were designed as control experiments, exploring different initial ventilation configurations without any ventilation tactics by the fire department. Experiments 1C, 1D, and 1E had the same initial ventilation configuration as Experiment 1A, with the addition of horizontal ventilation of the fire room (bedroom) window. Horizontal ventilation occurred shortly prior to suppression. Experiment 1D also included door control of the fire apartment door during suppression, and hydraulic ventilation after suppression. In Experiment 1E, the bedroom (fire room) door closed during the fire growth stage, further limiting ventilation to the fire. Table 2.3 summarizes initial configurations and ventilation tactics used for the experiments in Scenario 1.

Table 2.3: Summary of Scenario 1 Experiments

Exp.	Ignition Location	Initial Vents Open	Ventilation Tactic
1A	Lower-Level Bedroom	None	None
1B	Lower-Level Bedroom	Apartment Door	None
1C	First-Floor Bedroom	None	Horizontal
1D	First-Floor Bedroom	None	Horizontal, Door Control, Hydraulic
1E	First-Floor Bedroom	None	Closed Fire Room Door

2.2.2 Scenario 2: First-Floor Bedroom Fires, Fire Showing

Scenario 2 was defined as the interior suppression of a first-floor bedroom fire with fire showing from the exterior. Prior to ignition, the bedroom window was removed, and all other exterior doors and windows were closed, including doors to other apartments in the structure. Firefighter intervention began after the bedroom transitioned to flashover. Scenario 2 included two experiments designed to compare the impact of positive pressure attack (PPA) to positive pressure ventilation (PPV).

Experiment 2A explored the effect of PPV: A fan placed at the exterior door was activated after suppression was completed to remove smoke from the structure. In addition, door control was used at the fire apartment door during suppression. The effect of PPA was explored in Experiment 2B in which a fan placed at the exterior door was activated at the start of suppression. Table 2.4 summarizes initial configurations and ventilation tactics used for the two experiments in Scenario 2.

Table 2.4: Summary of Scenario 2 Experiments

Exp.	Ignition Location	Initial Vents Open	Ventilation Tactic	Suppression
2A	First-Floor Bedroom	Bedroom Window	PPV, Door Control	Interior
2B	First-Floor Bedroom	Bedroom Window	PPA	Interior

2.2.3 Scenario 3: First-Floor Kitchen Fires, Fire Showing

Scenario 3 was defined as a first-floor kitchen fire with fire showing from the exterior. Prior to ignition, the living room sliding glass door was open, and all other exterior doors and windows were closed, including doors to other apartments in the structure. Horizontal ventilation was provided by the failure of the kitchen window followed by breaking the living room sliding glass door. Scenario 3 included two experiments designed to compare the effectiveness of interior suppression to a combination of interior and exterior suppression.

Experiment 3A evaluated the impact of interior suppression. In Experiment 3B, suppression began from the exterior with water applied through the kitchen window, then through the sliding glass door to the living room. Then the suppression crew advanced the hoseline into the structure for interior suppression. Table 2.5 summarizes initial configurations and ventilation tactics used for the two experiments in Scenario 3.

Table 2.5: Summary of Scenario 3 Experiments

Exp.	Ignition Location	Initial Vents Open	Ventilation Tactic	Suppression
3A	First-Floor Kitchen	Sliding Glass Door	Horizontal	Interior
3B	First-Floor Kitchen	Sliding Glass Door	Horizontal	Exterior, Interior

2.2.4 Scenario 4: Second-Floor Kitchen Fires, Fire Showing

Scenario 4 was defined as a second-floor kitchen fire with fire showing from the exterior. Prior to ignition, the living room sliding glass door was open, and all other exterior doors and windows were closed, including doors to other apartments in the structure. Horizontal ventilation of the kitchen window occurred before suppression. Scenario 4 included two experiments designed to compare the effectiveness of interior suppression to a combination of interior and exterior suppression.

Experiment 4A evaluated the impact of interior suppression. In Experiment 4B, suppression began from the exterior with water applied through the sliding glass door to the living room. Then the suppression crew advanced the hoseline into the structure for interior suppression. Table 2.6 summarizes initial configurations and ventilation tactics used for the two experiments in Scenario 4.

Table 2.6: Summary of Scenario 4 Experiments

Exp.	Ignition Location	Initial Vents Open	Ventilation Tactic	Suppression
4A	Second-Floor Kitchen	Sliding Glass Door	Horizontal	Interior
4B	Second-Floor Kitchen	Sliding Glass Door	Horizontal	Exterior, Interior

2.2.5 Scenario 5: Lower-Level Living Room Fire, Interior Fire Spread

Scenario 5 included one experiment that was designed to explore fire spread from a lower-level apartment through the common stairwell into second-floor apartments. Prior to ignition, the door to the lower-level apartment (Apartment J) and to two second-floor apartments (Apartments H and F) were open. The only exterior opening was the sliding glass door to the lower-level apartment (Apartment J). All other exterior doors and windows were closed, including doors to other apartments in the structure. Ignition occurred in the living room of the lower-level apartment (Apartment J).

Two ventilation changes were made before the start of suppression. First, the door to one of the second-floor apartments (Apartment H) was closed to explore the impact of isolating an apartment during the fire. The second ventilation change was opening the sliding glass door of the other second-floor apartment (Apartment F), providing an exhaust for the flow of combustion gases through the stairwell.

Interior and exterior suppression were both employed to fight the fire. Interior suppression began first, with the crew entering the exterior breezeway door and advancing toward the fire apartment on the lower-level. Concurrently with interior suppression, water from the exterior was applied through the fire apartment sliding glass door. Table 2.7 summarizes initial configurations and ventilation and suppression tactics used for the experiment in Scenario 5.

Table 2.7: Summary of Scenario 5 Experiment

Exp.	Ignition Location	Initial Vents Open	Ventilation Tactic	Suppression
5	Apt. J Living Room	Apt. Doors: J, H, F, Apt. J Sliding Door	Close Apt. H Door, Open Apt. F Sliding Door	Interior, Exterior

2.2.6 Scenario 6: Lower-Level Living Room Fire, Exterior Fire Spread

Scenario 6 included one experiment designed to explore fire spread from a lower-level apartment to first- and second-floor apartments directly above the fire apartment via the exterior. Prior to ignition, the sliding glass doors to the lower-level apartment (Apartment I) and the second-floor apartment (Apartment G) were open. All other exterior doors and windows were closed, including doors to other apartments in the structure. Ignition occurred in the living room of the lower-level apartment (Apartment I).

Two ventilation changes occurred before the start of suppression. The first was manually venting the kitchen window of the fire apartment to facilitate fire growth. The second was the failure of the sliding glass door of the first-floor apartment (Apartment C).

Exterior suppression was applied to the exterior fire spread and through the sliding glass door of the fire apartment. Table 2.8 summarizes initial configurations and ventilation and suppression tactics used for the experiment in Scenario 6.

Table 2.8: Summary of Scenario 6 Experiment

Exp.	Ignition Location	Initial Vents Open	Ventilation Tactic	Suppression
6	Apt. I Living Room	Apt. I Sliding Door	Horizontal	Exterior

2.3 Experimental Procedure

To conduct each of the experiments discussed in this report, a series of procedures was performed prior to, during, and after each fire. Prior to the start of each experiment, all UL FSRI and partnering fire service personnel were briefed on the necessary actions to be performed and likely events to occur during the fire. Crews were walked through the structure to ensure familiarity with the layout and instrumentation locations. All personnel donned necessary PPE and SCBA, deployed hoselines, and checked appropriate flow and pressure. FSRI personnel performed final instrument checks and prepared the ignition package. A final walkthrough of the structure was performed by the UL FSRI incident commander to ensure no personnel were located on the interior. Depending on the expected fire size, location, and extension potential, the number of crews varied. At a minimum, a single crew of four personnel was utilized for suppression and a single crew of four personnel was utilized for ventilation and/or secondary suppression actions. A standby crew for rapid intervention was present in each experiment. Two safety officers were also utilized during each experiment, typically located on the front and rear of the structure. UL FSRI research staff accompanied firefighting crews during operations. Additionally, weather was continuously monitored in case adverse conditions would present a safety hazard to personnel operating, in which case testing would be delayed.

During the experiments, communication between fire service personnel and UL FSRI staff was handled via fire department radios. The primary hoseline utilized in each experiment was 200 ft of 1 3/4 in. diameter hose. Nozzle selection varied between combination and smooth bore. The combination nozzle was set to flow 150 gpm at 50 psi and the smooth bore nozzle was a 7/8 in. tip set to flow 160 gpm at 50 psi.

As each experiment concluded, a fan was placed at the entry door to the enclosed stairwell and apartments were vented to help remove trapped smoke not exhausted during the experiment. The fan was a 24 in. gasoline-powered positive pressure ventilator. It was placed at 6 ft back from the entry door at full-tilt (approximately 20 deg.). Once the building was exhausted of remaining smoke, the UL FSRI incident commander performed a walkthrough of the structure with gas meter to determine if the air present had returned to ambient, pre-experiment levels.

2.4 Instrumentation

The apartment buildings in these experiments were instrumented to measure gas temperature, differential pressure, gas velocity, and gas concentrations, and hose streams were instrumented to measure suppression flow rates. Instruments utilized during the experiments included thermocouples, pressure transducers, bi-directional probes, gas analyzers, and water flow meters.

Gas temperatures were measured with 0.05 in. bare-bead, chromel-alumel (type K) thermocouples and 0.0625 in. inconel-sheathed thermocouples. Small-diameter thermocouples were used during these experiments to limit the impact of radiative heating and cooling. The expanded uncertainty associated with the temperature measurements from these experiments is estimated to be $\pm$ 15% as reported by researchers at NIST [23, 24]. Thermocouple arrays were used to provide vertical temperature profiles for different rooms throughout the test structure. The thermocouple arrays consisted of eight 0.05 in. (1.3 mm) bare-bead, chromel-alumel (type K) thermocouples with the top thermocouple located 1 in. below the ceiling. The remaining seven thermocouples were spaced in 1 ft intervals below the ceiling such that the bottom thermocouple was 7 ft below the ceiling and 1 ft above the floor. The ceilings in the living rooms of the second floor apartments were 11 ft high, and thus required thermocouple arrays with 11 thermocouples arranged with the same spacing as the 8 ft thermocouple arrays.

Pressure measurements were made using differential pressure sensors to determine pressure rise or drop relative to ambient (outside the structure) conditions. The pressure taps consisted of 1/4 in.

copper tubing connected to one side of a differential transducer. The other side was exposed to ambient conditions. Each pressure tap was installed 6 in. off the wall and 4 ft above the floor in both the stairwells and apartments. The differential pressure sensors had an operating range of ± 250 Pa. The expanded uncertainty associated with pressure measurements obtained from the transducers is estimated at ± 10% [25].

Sheathed thermocouples were paired with pressure transducers connected to bi-directional probes to measure gas velocity. Sheathed thermocouples allowed the instrumentation to be placed in areas where suppression streams might impact the thermocouples to minimize the affect the water had on the measurement. Chromel-alumel (type K), 0.0625 in. (1.6 mm) inconel-sheathed thermocouples were used. The pressure measurements (part of the velocity sensor package) were made using differential pressure sensors (with an operating range of ± 125 Pa) connected to each side of the bi-directional probe. The arrays consisted of five evenly spaced bi-directional probes and thermocouples. The bottom bi-directional probe and thermocouple were 4 in. above the ground, and the remaining four were spaced in 18 in. intervals above the first, such that the top placement was 76 in. above the ground and 4 in. below the top of the doorway. 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 [26].

Gas concentration sampling ports were installed in the structures. The sampling ports consisted of 3/8 in. stainless steel tubing within the structure. Once outside the structure, the sample was filtered through a coarse, 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 fine, 1 micron filter. To minimize transport time through the system, samples were pulled from the structure through the use of vacuum/pressure diaphragm pump rated at 0.75 CFM. Gas samples were analyzed through oxygen analyzers (paramagnetic alternating pressure) and combination carbon monoxide/carbon dioxide analyzers (non-dispersive infrared). The gas sampling instruments used throughout the series of tests discussed in this report have demonstrated an expanded uncertainty of ± 1% when compared to span gas volume fractions [27]. Given the non-uniformities and movement of the fire gas environment and the limited set of sampling points in these experiments, an estimated expanded uncertainty of ± 12% is applied to the results [28]. Each sampling port was installed 4 ft above the respective floor in the stairwell and in the apartment of interest.

Hoseline water flow measurements were obtained from electromagnetic flow meters. A flow meter was installed downstream of the engine but upstream of the nozzle, at a coupling, to monitor the flow of water through the hoseline. Flow meters were used prior to the experiment to set flow rates at approximately 160 gpm for 7/8 in. smooth bore nozzles and 150 gpm for combination nozzles to identify periods of water flow, and to measure the cumulative water use over the course of the experiment. The expanded uncertainty associated with water flow rate measurements is ± 11% [9].

2.4.1 Measurement Locations

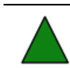
The instrumentation locations were the same in each of the four buildings used in the experiments. Figures 2.7, 2.8, and 2.9 show the locations of the instrumentation on each floor of the test structures. Each experiment used a different subset of the available instrumentation, which are specified in Section 3.

The fire apartment in each experiment consisted of the following instrumentation. There was a thermocouple array and a pressure tap located in each of the three main rooms: the bedroom, kitchen, and living room. An array of bi-directional probes and sheathed thermocouples were installed in the doorway at the entrance to the apartment. A gas sampling port was located next to the thermocouple array in the living room. Experiments 5 and 6 were exceptions in that the fire apartments did not have gas sampling probes installed. Instead, gas sampling probes were located in the living rooms of the second-floor apartments (i.e., Apartment F in Experiment 5, Apartment G in Experiment 6).

The stairwells included the same instrumentation in every experiment. Each floor of the stairwell included a thermocouple array, a gas sampling probe, and a pressure tap.

Several experiments utilized additional instrumentation installed in apartments other than the fire apartment. Any instrumentation installed in these apartments matched the locations used in the fire apartment. Details on what instrumentation was included for each experiment are provided in Section 3.

Table 2.9: Instrumentation Legend

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

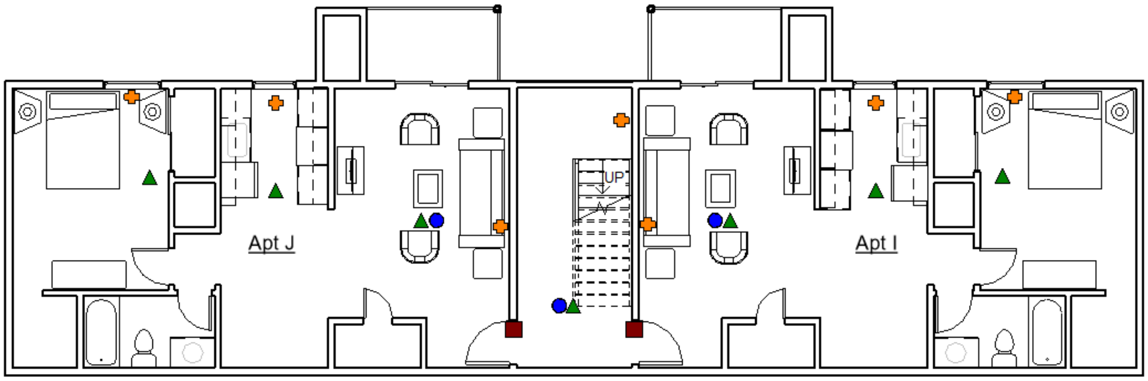


Figure 2.7: Instrumentation arrangement for the lower level.

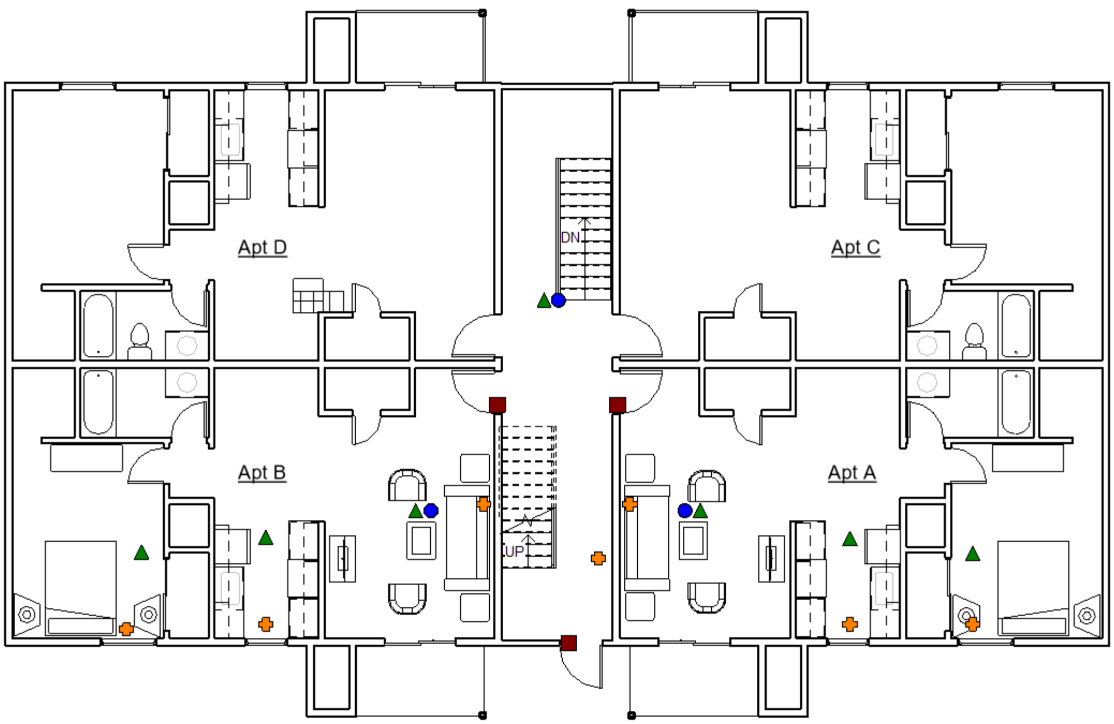


Figure 2.8: Instrumentation arrangement for the first floor.

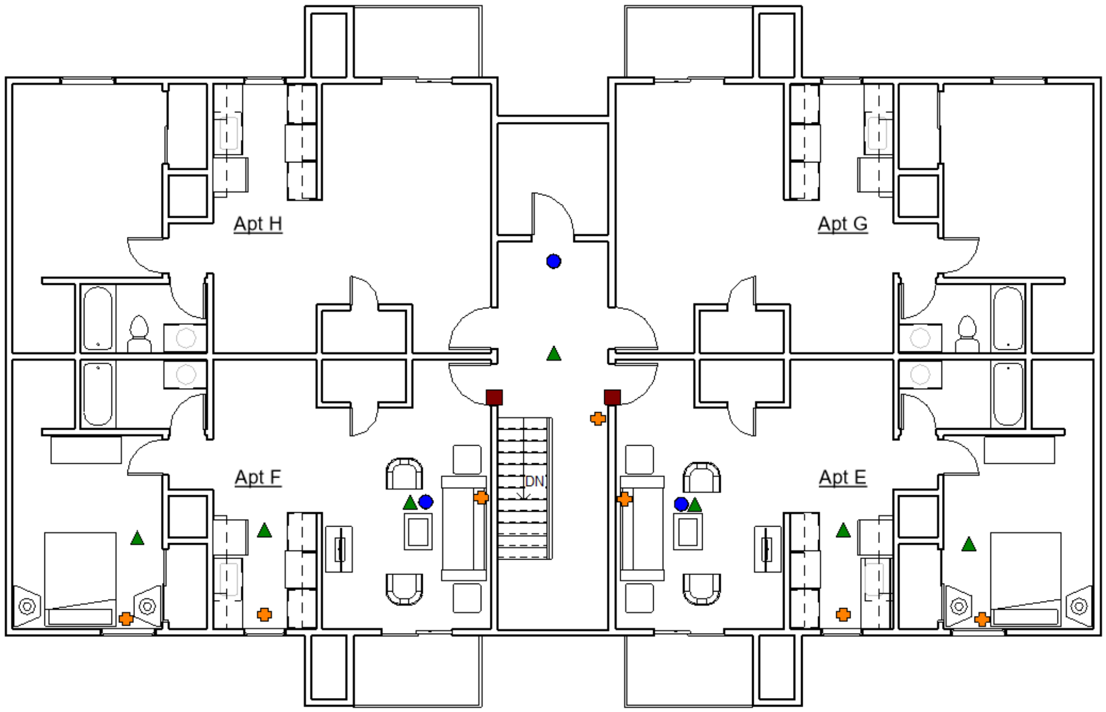
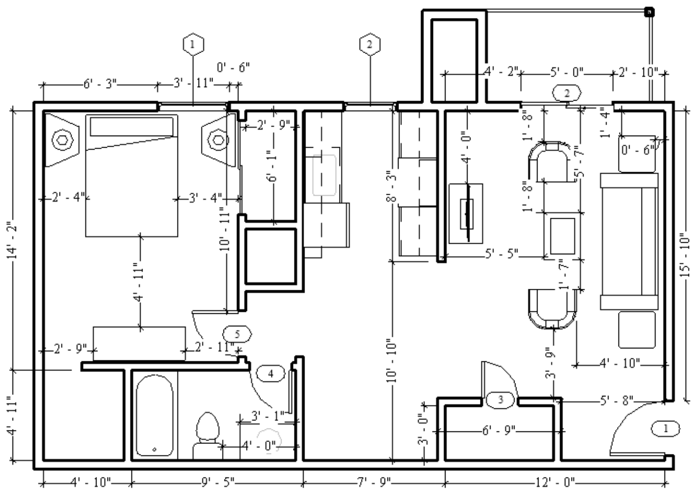


Figure 2.9: Instrumentation arrangement for the second floor.

2.5 Fuel Packages

A consistent fuel package comprised of residential furnishings was used in each apartment for this series of experiments. The overall arrangement and dimensions of a representative furnished apartment is presented in Figure 2.10.



Door Schedule		
Mark	Height	Width
1	6' - 8"	3' - 0"
2	6' - 8"	5' - 0"
3	6' - 7 1/2"	2' - 0"
4	6' - 7 1/2"	2' - 4"
5	6' - 7 1/2"	2' - 6"

Window Schedule			
Mark	Sill Height	Height	Width
1	1' - 11"	4' - 10"	3' - 11"
2	1' - 11"	4' - 11"	2' - 11 1/2"

Figure 2.10: Dimensions of a representative fire apartment with a complete fuel load.

The furnishings were measured and weighed, and the base materials used in their construction were determined and documented. The furnishings specific to the bedroom, kitchen, and living room fuel packages are presented in Sections 2.5.2–2.5.4 along with representative photographs.

2.5.1 Ignition Fuels

For each experiment, ignition was initiated remotely via an electric match. This involved coiled 28 gauge (0.32 mm) nichrome wire placed through the match heads of a standard matchbook. The nichrome wire was then connected to an extension cord leading to a 24 volt power supply located with the data acquisition hardware. When the countdown to ignition occurred, power was sent to the matchbook, through electric current, and ignited the match heads, and subsequently the adjacent fuel.

For bedroom and kitchen fires, the electric match was placed into a 5.5 gal (21 L) polypropylene waste container. The waste container weighed 1.5 lbs (0.7 kg) on average and was 16.0 in. (40.6 cm) tall. A 1.0 in. (2.5 cm.) diameter hole was cut into the center of one side of the waste container approximately 1.0 in. (2.5 cm) above the bottom of the container to provide access for the electric match. The waste container was filled with five full sheets of crumpled newspaper and a total of 27 9 oz (266 mL) wax paper cups.

This ignition source can be seen in Figure 2.11. Fuel characterization testing was performed on the ignition package, and the maximum heat release rate for this fuel was determined to be 60 kW.

(a) Waste Container Fuel Package

(b) HRR Testing of Waste Container

Figure 2.11: Images of ignition setup and heat release rate testing for the bedroom and kitchen fires.

For ignitions in the bedroom, the waste container was placed next to the head of the bed, as shown in Figure 2.12a. Two waste containers were used for ignitions in the kitchen, each with an electric match. One was placed on the floor and the other on the counter. In addition, four 283.5 g (10 oz) bags of potato chips were arranged around the waste containers. Figure 2.12b shows an example of the setup for a kitchen ignition.

(a) Bedroom

(b) Kitchen

Figure 2.12: Images of example setups for ignitions in the bedroom and kitchen.

For experiments in which ignition occurred in the living room, the electric match was placed on the sofa cushion next to the arm support, as pictured in Figure 2.13. To increase the reliability of ignition and support the propensity for flame spread, a small cut in the fabric (about 6 in. long) was made in the back cushion to expose the polyester batting.

Figure 2.13: Images of an example setup for ignitions in the living room.

2.5.2 Bedroom Fuel Package

Bedroom fuel loads consisted of a queen-size mattress (including two small and two large pillows, sheets, and a comforter), a queen-size box spring and metal frame, two night stands, a full-size horizontal dresser, two lamps, curtains for the bedroom window, and existing carpeted flooring. The items were arranged in the space based on the configuration of the room. Photographs of representative bedroom fuels are presented in Figure 2.14.

Figure 2.14: Images of a representative bedroom fuel load.

Table 2.10 provides the primary materials of each of the fuel items and Table 2.11 provides the dimensions and weights of each item.

Table 2.10: Description of materials that comprised the items in the bedroom fuel load.

Item	Material
Mattress	polyurethane foam over wrapped coil spring design
Box Spring	fabric over wood frame with steel support grid
Mattress Topper	100% polyurethane foam (4 in. depth)
Flat Sheet	100% polyester
Fitted Sheet	100% polyester
Comforter	100% polyester
Large Pillows	polyurethane fill with polyester cover
Small Pillows	polystyrene
Night Stand	wood frame with plastic veneer covered particle board surfaces, wood drawer
Dresser	wood frame with plastic veneer covered particle board top, wood drawers
Lamp	metal base and stand
Lamp Shade	fabric over wire frame
Carpet	polyester carpet fiber with polypropylene backing
Carpet Padding	100% polyurethane foam

Table 2.11: Dimensions and weights of items in the bedroom fuel load.

Item	Length [in.] (cm)	Width [in.] (cm)	Height [in.] (cm)	Weight [lb] (kg)
Mattress	80.0 (203.0)	60.0 (152.4)	8.0 (20.3)	61.8 (28.1)
Box Spring	80.0 (203.0)	60.0 (152.4)	9.0 (22.9)	53.0 (24.1)
Mattress Pad	80.0 (203.0)	60.0 (152.4)	3.0 (7.6)	14.3 (6.5)
Flat Sheet	106.0 (269.0)	90.0 (229.0)		1.1 (0.5)
Fitted Sheet	80.0 (203.0)	60.0 (152.4)		1.1 (0.5)
Comforter	92.0 (234.0)	88.0 (223.5)		4.2 (1.9)
Pillows	27.0 (68.6)	14.0 (35.6)	7.0 (17.8)	3.96 (1.8)
Small Pillows	20.0 (50.8)	11.0 (28.0)	6.0 (15.2)	0.77 (0.35)
Night Stand	35.0 (89.0)	22.0 (56.0)	24.0 (63.3)	35.2 (16.0)
Dresser	60.0 (152.4)	22.0 (56.0)	37.5 (95.3)	241.1 (109.6)
Lamp	10.0 (25.4)	10.0 (25.4)	13.0 (33.0)	3.1 (1.4)
Lamp Shade	18.0 (45.7)	9.0 (22.9) top	13.0 (33.0)	0.67 (0.3)
Carpet	164.0 (416.6)	128.0 (325.1)	0.5 (1.3)	42.8 (19.5)
Carpet Padding	164.0 (416.6)	128.0 (325.1)	0.38 (1.0)	24.6 (11.2)

2.5.3 Kitchen Fuel Package

The kitchen fuel packages included pre-installed and existing cabinetry, counter tops, an electric range, a refrigerator, and a dishwasher. Photographs of a representative kitchen is presented in Figure 2.15. A detailed kitchen kitchen layout, including dimensions of cabinets and appliances, is presented in Figure 2.10.

Figure 2.15: Image of a representative kitchen fuel load, which included cabinetry, counters, a range, a refrigerator, and a dishwasher.

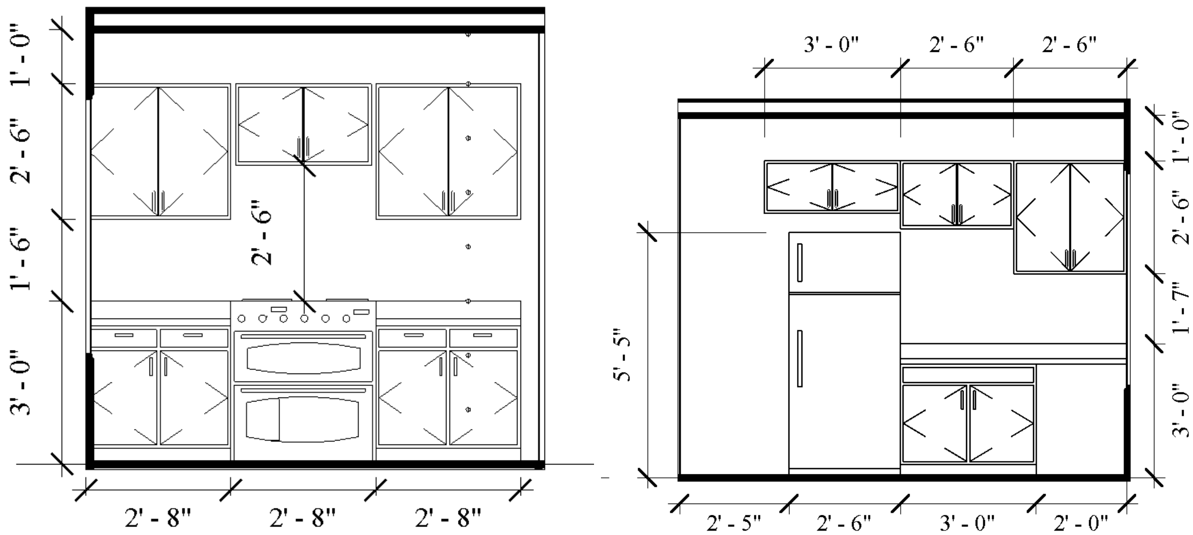


Figure 2.16: Dimensions of the furnishings in the kitchen fuel load.

2.5.4 Living Room Fuel Package

The living room fuel load was comprised of a sofa, two barrel chairs, a coffee table, two end tables, a TV stand, a TV, and existing carpet and carpet padding. The items were arranged in the space based on the configuration of the room. Photographs of representative living room fuels are presented in Figure 2.17. Tables 2.12 and 2.13 provide the materials and dimensions of each item, respectively.

Figure 2.17: Image of a representative living room fuel load, which included a sofa, two barrel chairs, a coffee table, two end tables, a TV stand, and a TV.

Table 2.12: Description of materials that comprised the items in the living room fuel load.

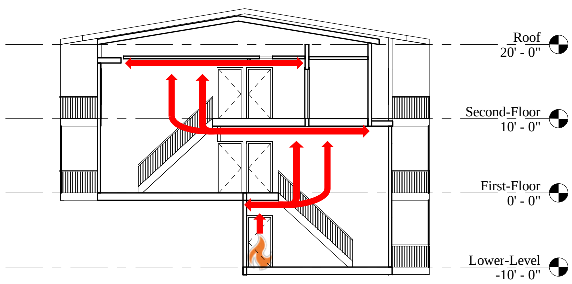
Item	Material
Sofa:	
Seat cushions	74% polyurethane foam, 26% polyester batting
Body	71% polyester fiber, 29% batting, engineered wood frame with metal springs under cushions
Barrel Chair	expanded polystyrene frame, polyurethane cushion and padding, polyester fabric
Coffee Table	wood frame and veneer-covered MDF top
End Table	wood frame and veneer-covered MDF top
TV Stand	wood frame with plastic veneer covered particle board top surface
TV	plastic and glass
Carpet	polyester carpet fiber with polypropylene backing
Carpet Padding	100% polyurethane foam

Table 2.13: Dimensions and weights of items in the living room fuel load.

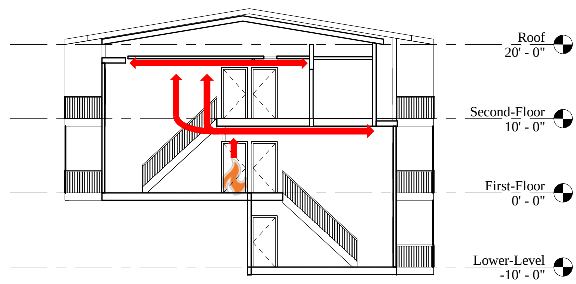
Item	Length [in.] (cm)	Width [in.] (cm)	Height [in.] (cm)	Weight [lb] (kg)
Sofa	86.6 (220.0)	37.4 (95.0)	34.7 (88.0)	102.7 (46.7)
Barrel Chair	30.7 (78.0)	27.6 (70.0)	30.7 (78.0)	21.3 (9.7)
Coffee Table	36.0 (91.4)	20.0 (50.8)	17.0 (43.2)	30.1 (13.7)
End Table	26.0 (66.0)	22.0 (55.9)	24.0 (61.0)	27.5 (12.5)
TV Stand	39.0 (99.1)	22.0 (55.9)	31.5 (80.0)	82.5 (37.5)
TV	36.0 (91.4)	6.8 (17.2)	24.0 (61.1)	6.8 (13.6)
Carpet	190.0 (483.0)	144.0 (366.0)	0.5 (1.3)	55.9 (25.4)
Carpet Padding	190.0 (483.0)	144.0 (366.0)	0.38 (1.0)	32.1 (14.6)

3 Results

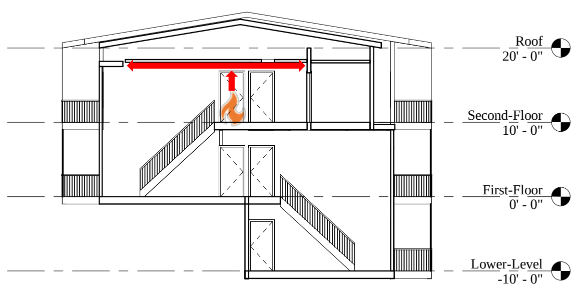
Due to the overall size and nature of the structure configuration, understanding the smoke and fire gas spread in the stairwell is an important first step to adding context to some of the experimental results presented below. Figure 3.1 shows an approximation of how the smoke rose throughout the stairwell, ultimately filling from the top down, based on initial fire location.



(a) Lower-Level Fire



(b) First-Floor Fire



(c) Second-Floor Fire

Figure 3.1: Example gas spread in the enclosed stairwell based on initial fire location.

When the fire was located on the lowest level of the structure (see Figure 3.1a), the gases exhausted out the apartment and rose due to buoyancy. There was a short, cantilevered overhang present directly above the doorways to the lower-level apartments. The gases traveled across this surface until it ended and began vertically rising through the open space between the lower level and the first floor. At this point, the gases reached the underside of the second-floor landing and began to laterally spread across this surface, reaching the back (side C) wall and the end of the front overhang. Once again, they continued to rise vertically until they met the ceiling surface of the second-floor. Lateral spread brought the gases to the front (side A) wall and to the rear of the second-floor landing. Gases then began to fill the stairwell from the top down, first encompassing the second-floor landing area, followed by the first-floor, and eventually down to the lowest level of the structure.

When the fire originated on the first floor (see Figure 3.1b), the gases exhausted out the apartment and rose due to buoyancy. They reached the underside of the second-floor landing, spreading out laterally toward both the front (side A) and rear (side C) of the structure. As the gases reached the end of the front overhang, they rose vertically until reaching the ceiling surface of the second floor. Lateral spread brought gases to the front (side A) wall and rear of the second-floor landing, where accumulation began and the space filled from the top down.

For a fire on the second floor (see Figure 3.1c), the gases exhausted out of the apartment and rose, directly spreading across the ceiling surface of the landing and stairwell. Because this was the top floor of the stairwell, accumulation began immediately, filling from the top down.

When interpreting the results presented below, consider the measurement locations of gas temperature, pressure, and gas concentrations. Gas temperature was recorded every 1.0 ft vertically from the floor to the ceiling. Pressure and gas concentrations were single-point measurement locations 4.0 ft above the floor level. The lateral spacing within the stairwell (pictured in Figure 3.2) is also vital to understanding the results.

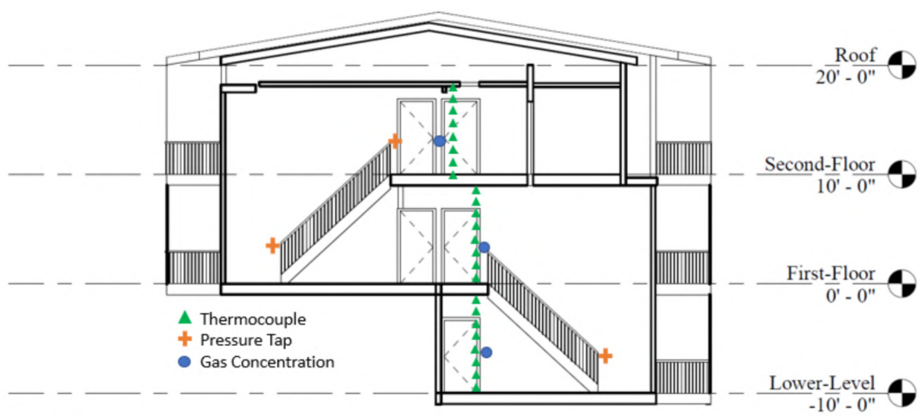
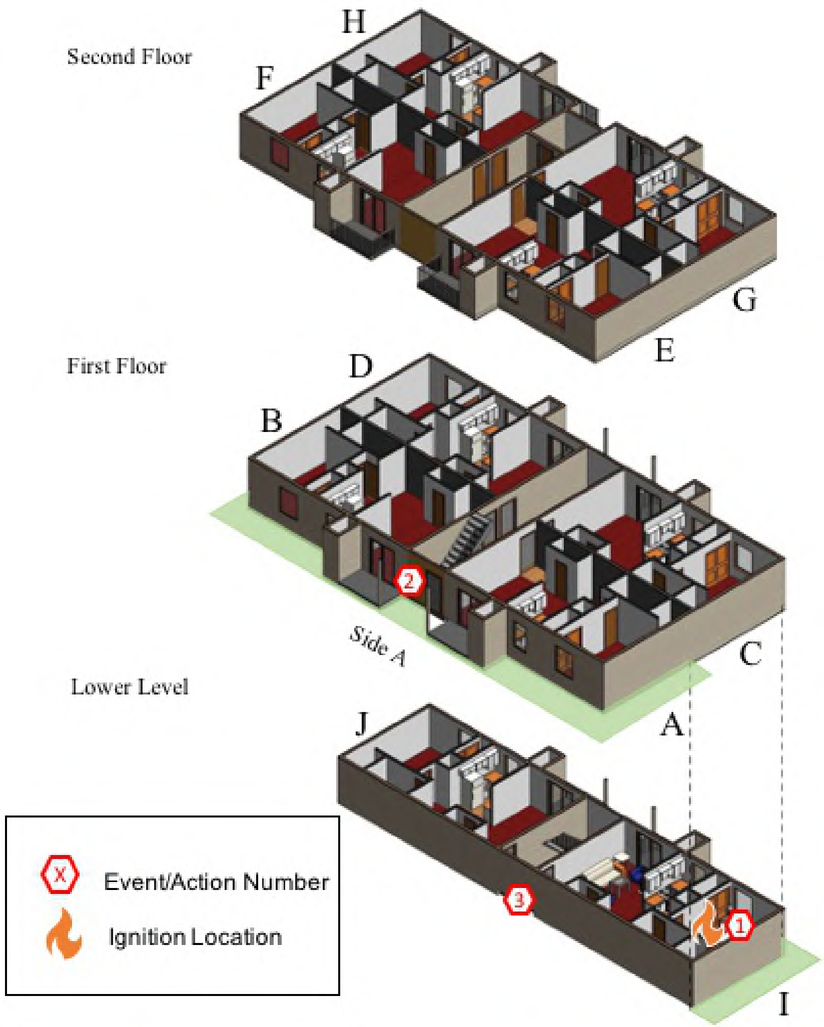


Figure 3.2: Approximate heights and locations of stairwell instrumentation.

3.1 Experiment 1A – Lower-Level Apartment Fire with Apartment Door Closed

Experiment 1A was conducted in Apartment I of 1980 Kimberly Village Lane, and was designed to evaluate fire development in the bedroom of a lower-level apartment. Prior to ignition, all exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was open for the duration of the experiment. There was minimal smoke and no fire showing on the exterior of the structure at the start of firefighter intervention. Firefighter intervention included entry to the structure, followed by entry into the fire apartment and suppression as needed. Figure 3.3 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Open exterior door	10:00	600
3	Open apartment door	11:28	688

Figure 3.3: Time and sequence of actions and events for Experiment 1A.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.4 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

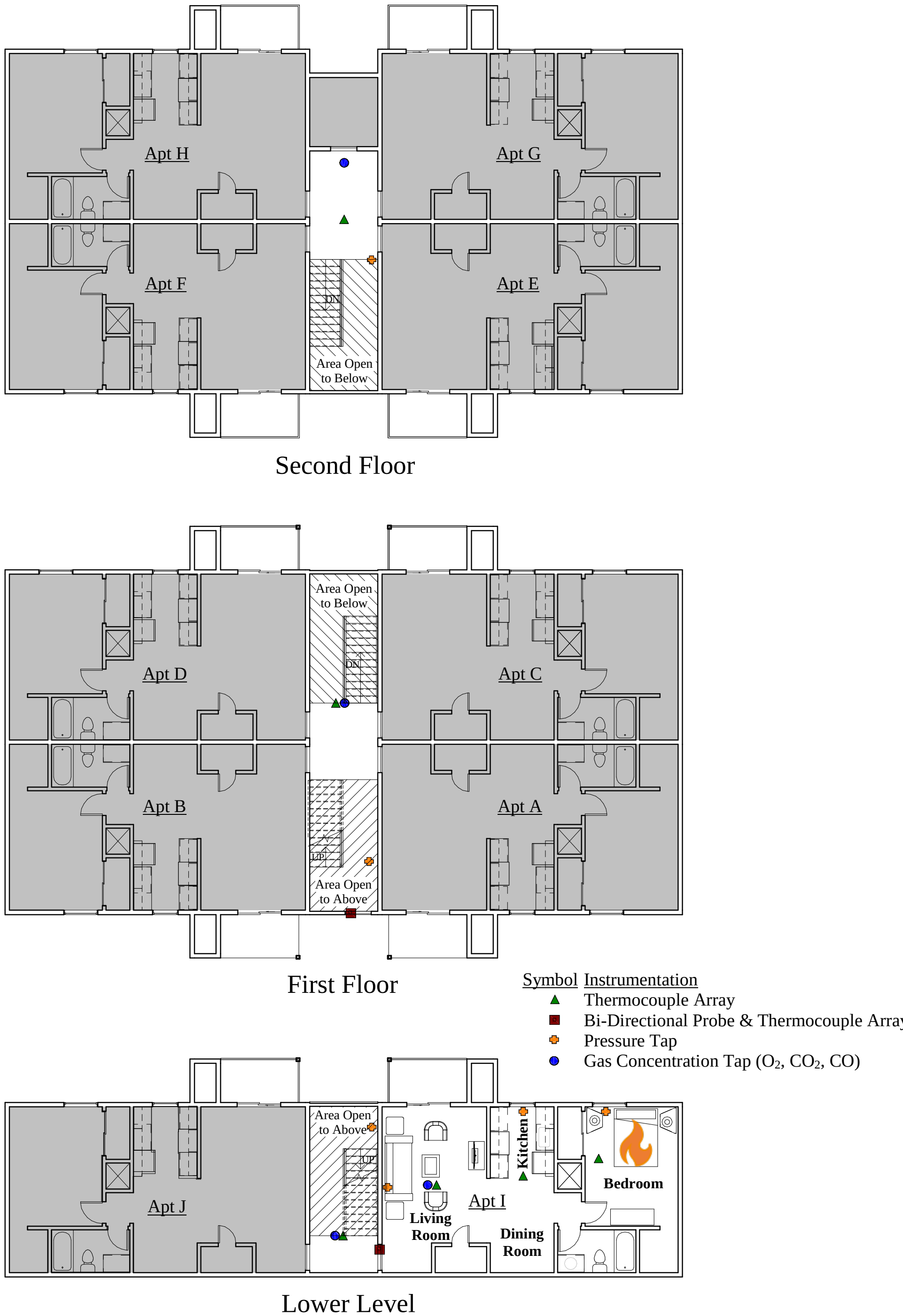


Figure 3.4: Instrumentation locations in Experiment 1A.

The bedroom, kitchen, and living room were furnished with the fuel loads described and photographed in Section 2.5.

The fire in Experiment 1A was ignited in a small, plastic waste container placed next to the head of the bed (t = 0 s). Fire growth was uninhibited in the fire apartment until the oxygen available for combustion was consumed. As the smoke layer in the fire room began to build and descend, the camera in the bedroom became obscured, and was completely dark by 240 s (6:00). Smoke became visible in the stairwell at 180 s (3:00) through normal leakage around the closed apartment door due to increased pressure in the fire compartment. Forty seconds later (at 220 s (3:40)), the smoke layer had descended to the living room floor. Zero visibility conditions remained until fire department interventions occurred.

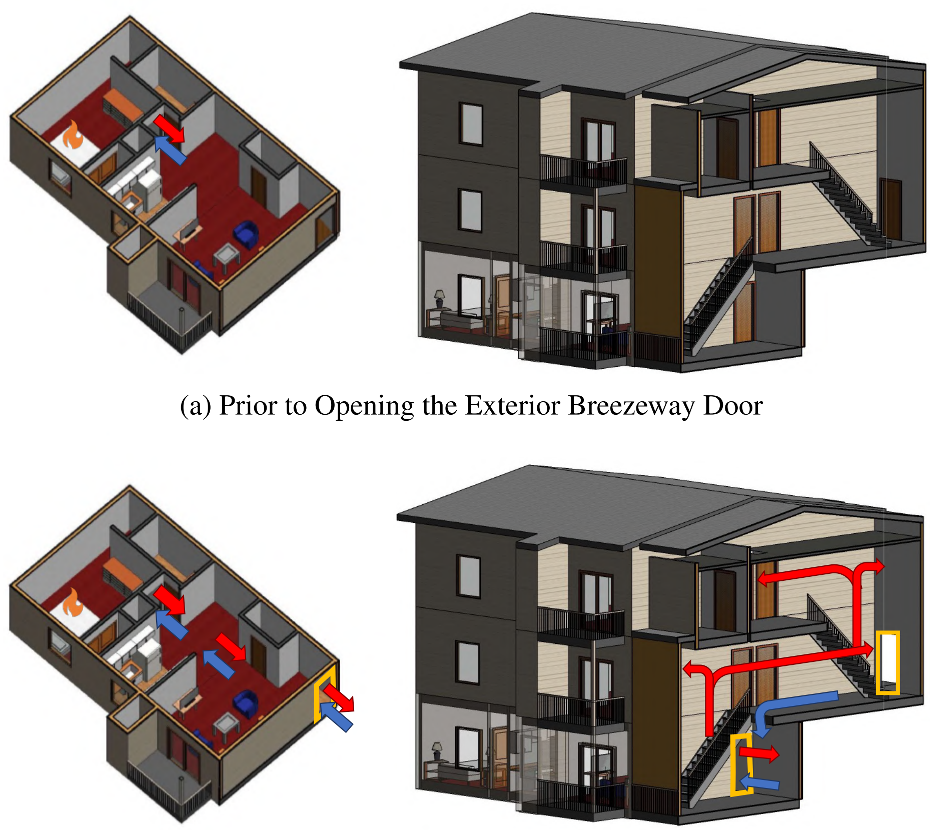
The first fire department intervention in Experiment 1A was the opening of the exterior breezeway door 600 s (10:00) post ignition. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded downstairs to the door of the fire apartment. The apartment door was opened at 688 s (11:28). There was no fire visible when the suppression crew made entry to the apartment. A 2.5 gallon Class A water extinguisher was used intermittently to extinguish hot spots. The absence of active fire made the hoseline unnecessary, and it was therefore not used during the experiment. The suppression crew found that the drywall ceiling of the bedroom (fire room) had failed prior to their entry to the compartment. It is unclear from the video when the bedroom ceiling failed, but it occurred sometime between 5 and 11 minutes post ignition. Pictures of the bedroom following the experiment are shown in Figure 3.5. The lack of thermal damage and soot deposition on the exposed joists suggests failure likely occurred late into the experiment.

(a) C/D Corner

(b) Side B

Figure 3.5: Post-test images of the fire room (bedroom) in Experiment 1A.

The flow of combustion gases and fresh air during Experiment 1A are sketched in Figure 3.6. As the fire grew in the bedroom, high temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the common space in the apartment (the kitchen, dining room, and living room). Entrainment from the fire plume caused air to be drawn through the bedroom doorway into the fire compartment, which led to further fire growth (see Figure 3.6a). The closed fire apartment door prevented combustion gases from exhausting into the stairwell, and fresh air from being entrained into the fire compartment. As a result, combustion gases filled the fire apartment until the fire apartment door was opened. When firefighters opened the fire apartment door, a new exhaust vent was created. The buoyant, higher pressure gases in the fire compartment rose through the stairwell. Gases filled the stairwell, and upon reaching the top of the doorway, flowed out the exterior breezeway door. Cooler, ambient air was entrained into the stairwell and fire apartment to replace the exhausting combustion gases (see Figure 3.6b). The fire, however, was already extinguished due to the lack of oxygen.

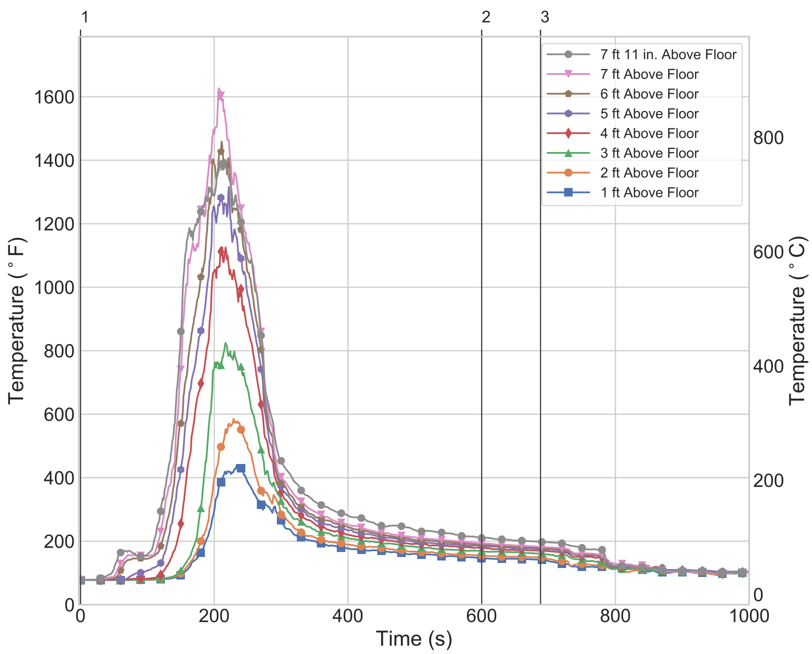


(a) Prior to Opening the Exterior Breezeway Door

(b) After Opening the Breezeway and Fire Apartment Door

Figure 3.6: Changes in gas flow during Experiment 1A. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

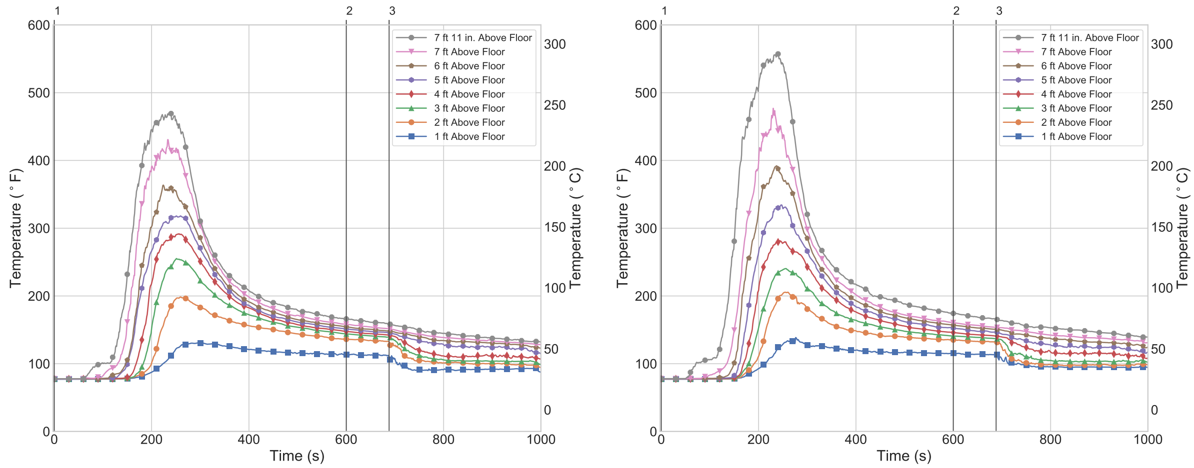
The time histories of the fire room temperatures are presented in Figure 3.7. Temperatures nearest the ceiling (6 ft above the floor and higher) in the fire room increased 1 min. after ignition. By 150 s (2:30) after ignition, temperatures at all elevations increased. At their peak, between 207 s (3:27) and 234 s (3:54) post-ignition, temperatures ranged from 1625 °F 1 ft below the ceiling to 440 °F 1 ft above the floor. Following a peak, temperature in the fire room then began a steady decrease, an indication the compartment became ventilation-limited. Temperatures at all elevations in the fire room dropped below 400 °F by 318 s (5:18). When the suppression crew entered the structure at 600 s (10:00), temperatures at all elevations in the fire room were below 200 °F.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

Figure 3.7: Fire room (bedroom) temperatures for Experiment 1A.

The temperatures in the kitchen and living room of the fire apartment showed a similar response as temperatures measured in the bedroom, but with lower magnitudes (see Figure 3.8). The peak temperatures were 555 °F in the kitchen and 470 °F in the living room. Both peaks were measured 1 in. below the ceiling, and occurred at 240 s (4:00). The temperature in both rooms then decreased in response to the compartment becoming ventilation-limited. When the suppression crew entered the structure at 600 s (10:00), temperatures at all elevations in both rooms were below 175 °F.

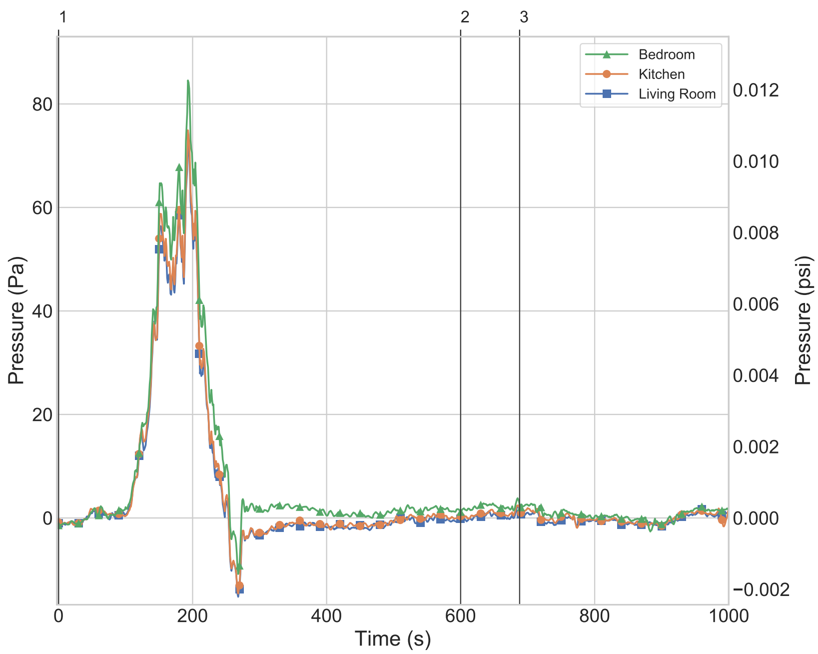


(a) Living Room (b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

Figure 3.8: Living room and kitchen temperatures for Experiment 1A.

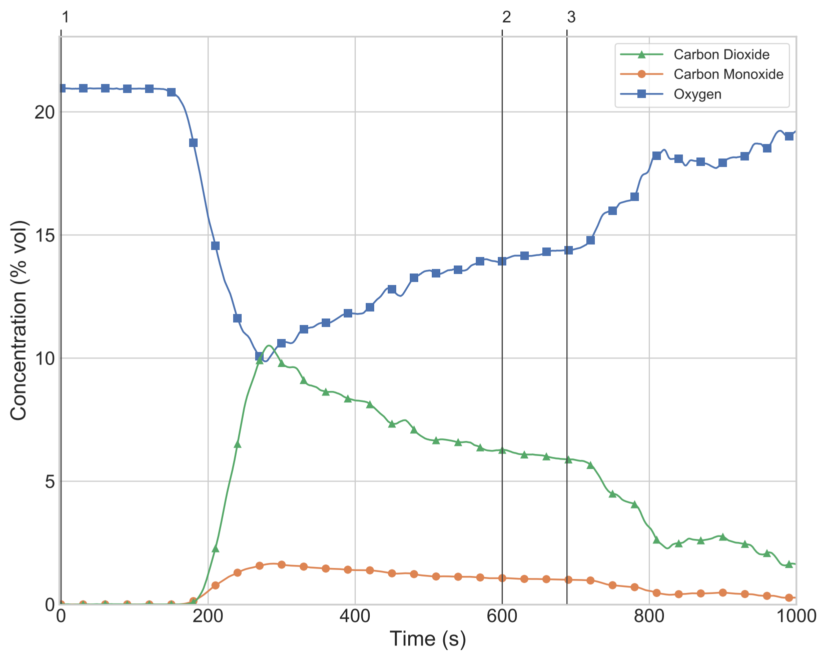
The pressure measurements in each room of the fire apartment had similar temporal profiles, though the bedroom pressure was slightly higher because it was the room of origin (see Figure 3.9). The pressure in each room of the fire apartment began increasing around 100 s (1:40) post-ignition. Each pressure peaked at 193 s (3:13), slightly earlier than when the temperatures in the fire apartment peaked. The peak pressures in the bedroom, kitchen, and living room were 85 Pa, 75 Pa, and 73 Pa, respectively. The temperature drop in the fire apartment resulted in gas contraction, which caused the pressures to become negative (below atmospheric). The pressures reached a minimum at 266 s (4:26), with values of -11 Pa in the bedroom and -15 Pa in both the kitchen and living room. The pressures then returned to approximately ambient conditions by around 300 s (5:00), where they remained for the rest of the experiment.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

Figure 3.9: Fire apartment pressures for Experiment 1A. Each pressure tap was installed 4 ft above the floor.

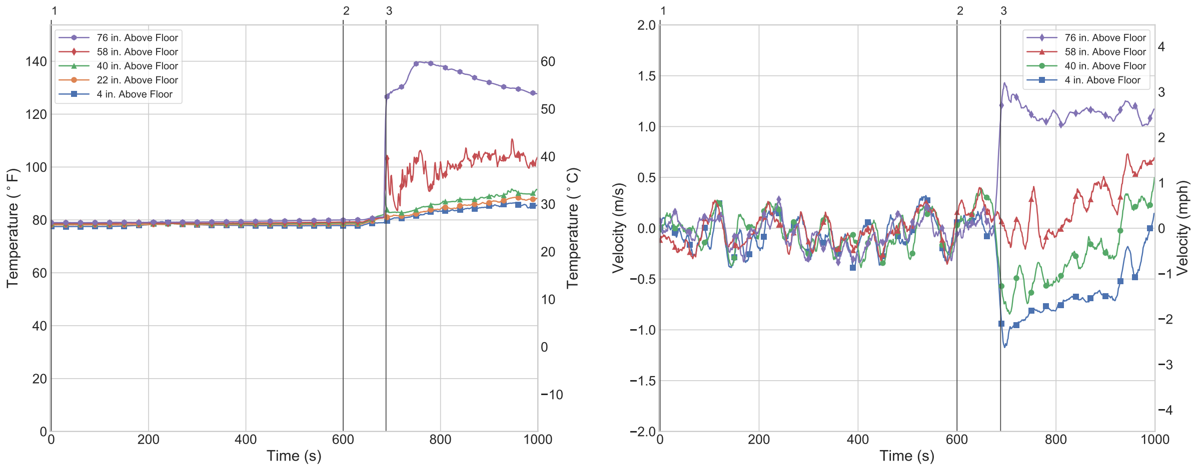
Gas concentrations were measured in the living room of the fire apartment (see Figure 3.10). Gas concentrations began to change in response to the fire growth at around 150 s (2:30). At oxygen (O_2) levels between 13% to 15%, flames will begin to self-extinguish [29, 30], and during this fire the O_2 concentration in the living room fell below 15% at 205 s (3:25). This time coincided with the timing of peak temperatures and pressures in the fire apartment and subsequent decrease in values as the fire transitioned to a ventilation-limited state. The O_2 concentration decreased to a minimum of 9.8% at 280 s (4:40). At the same time, the carbon monoxide (CO) and carbon dioxide (CO_2) concentrations reached maximums of 1.7% (17,000 ppm) and 10.5%, respectively. Gas contraction in the apartment (see Figure 3.9) led to a drop a pressure below ambient levels. Given that higher pressure always flows toward an area of lower pressure, air entered the apartment through cracks and crevices and gas concentrations then slowly began returning to ambient conditions, reaching 14.4% O_2, 1.0% (10,000 ppm) CO, and 5.9% CO_2 by the time firefighters entered the apartment at 680 s. Once the apartment door was opened, the rate at which gas concentrations returned to ambient levels increased until the conclusion of the experiment.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

Figure 3.10: Living room gas concentrations for Experiment 1A. Measurement location was 4 ft above the floor.

The apartment door was opened 600 s post ignition, which allowed the combustion gases in the fire apartment to flow into the stairwell. Figure 3.11 shows the temperatures and velocities recorded at the fire apartment door. After the suppression crew opened the apartment door, the higher temperature gases (>100 °F) flowed out of the apartment at approximately 1 m/s (2 mph) while below the 4 ft level, air flowed into the unit. This behavior aligned with the pressure measurements near ambient in the apartment at the 4 ft level following the open door. Note: The velocity probe 22 in. above the floor was damaged during the experiment and is therefore not included.



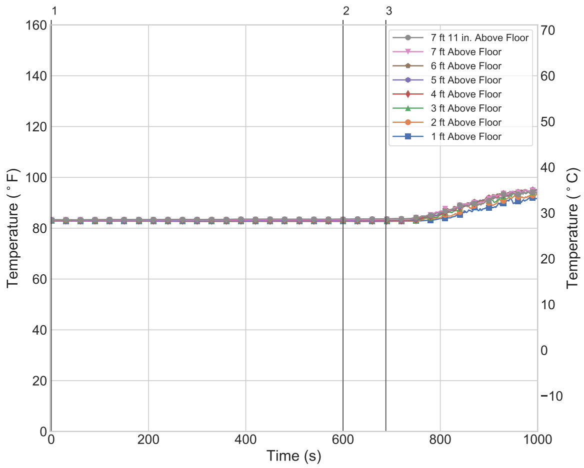
(a) Temperature

(b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

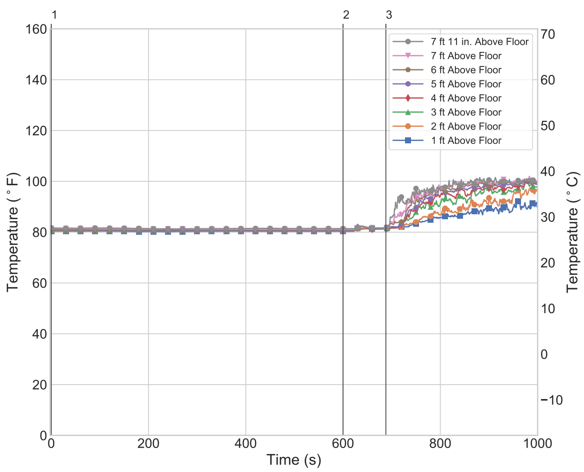
Figure 3.11: Apartment I door temperatures and velocities for Experiment 1A.

The temperatures measured on each floor of the stairwell remained ambient and steady (below 85 °F) until the door to the fire apartment was opened (see Figure 3.12). After the apartment door was opened, temperatures on each floor increased as smoke from the previously closed fire apartment door began to fill the stairwell. Peak temperatures measured on each floor in the stairwell did not exceed 120 °F. No measurable pressure increases were recorded in the stairwell during this experiment.

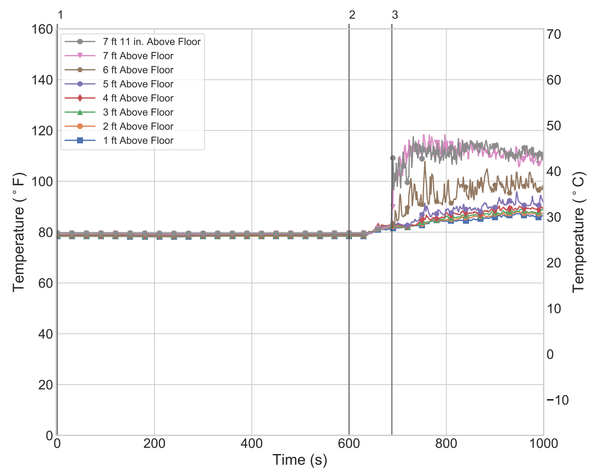


	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

(a) Second-Floor Stairwell



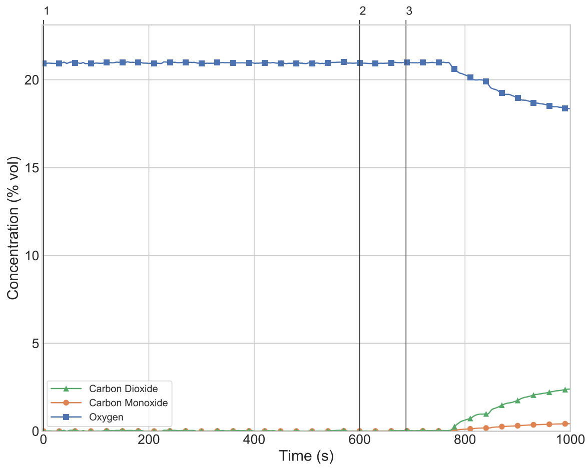
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

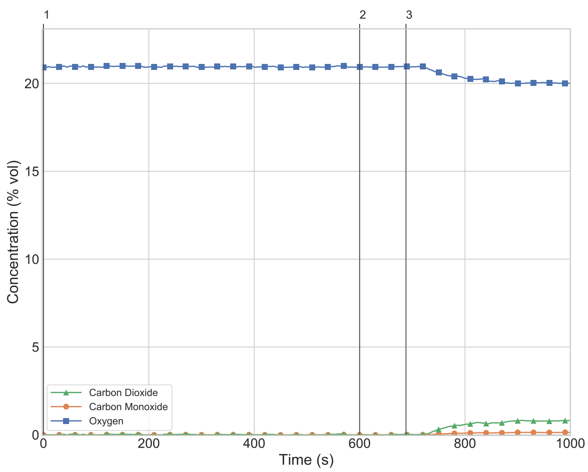
Figure 3.12: Stairwell temperatures for Experiment 1A.

The gas concentrations in the stairwell reflected ambient conditions until firefighters opened the door to the fire apartment (see Figure 3.13). Gas concentrations measured in the lower level were the first to respond, but the most noticeable response was measured on the second floor, where gas concentrations reached 18.4% O_2, 0.4% (4000 ppm) CO, and 2.4% CO_2, with buoyant smoke filling the stairwell from the top down. The change in measured concentrations was due to a combination of the higher pressure combustion gases displacing ambient air as well as mixing as the gases flowed through the stairwell.

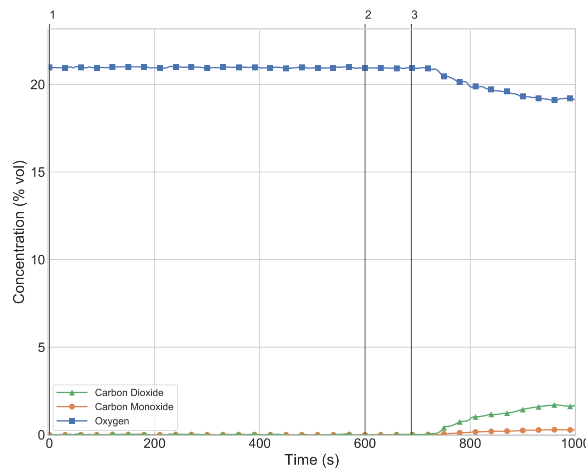


	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

(a) Second-Floor Stairwell



(b) First-Floor Stairwell

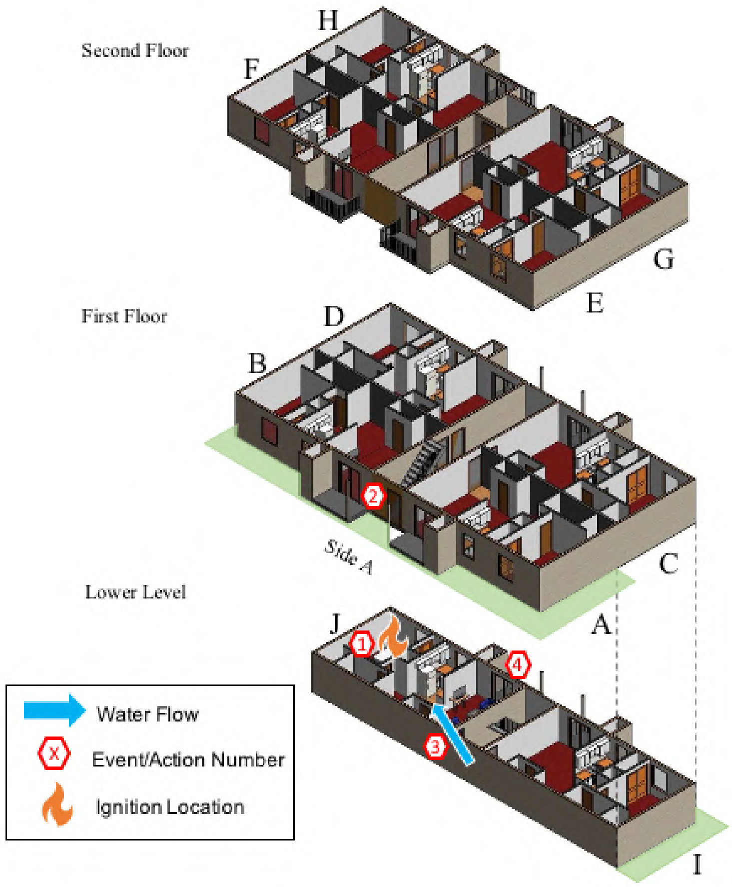


(c) Lower-Level Stairwell

Figure 3.13: Stairwell gas concentrations for Experiment 1A. Measurement locations were 4 ft above the floor.

3.2 Experiment 1B – Lower-Level Apartment Fire with Apartment Door Open

Experiment 1B was conducted in Apartment J of 1980 Kimberly Village Lane, and was designed to evaluate fire development in the bedroom of a lower-level apartment with the door from the apartment to the enclosed stairwell open. Prior to ignition, all exterior windows and doors were closed, including doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was open for the duration of the experiment. There was minimal smoke and no fire showing on the exterior of the structure at the start of firefighter intervention. Firefighter intervention included entry to the structure, followed by entry into the fire apartment and flow-and-move suppression into the fire compartment. Figure 3.14 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Open exterior door	10:00	600
3	Enter fire apartment; flow-and-move to fire room	11:00	660
4	Ventilate apartment	16:16	976

Figure 3.14: Time and sequence of actions and events for Experiment 1B.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.15 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

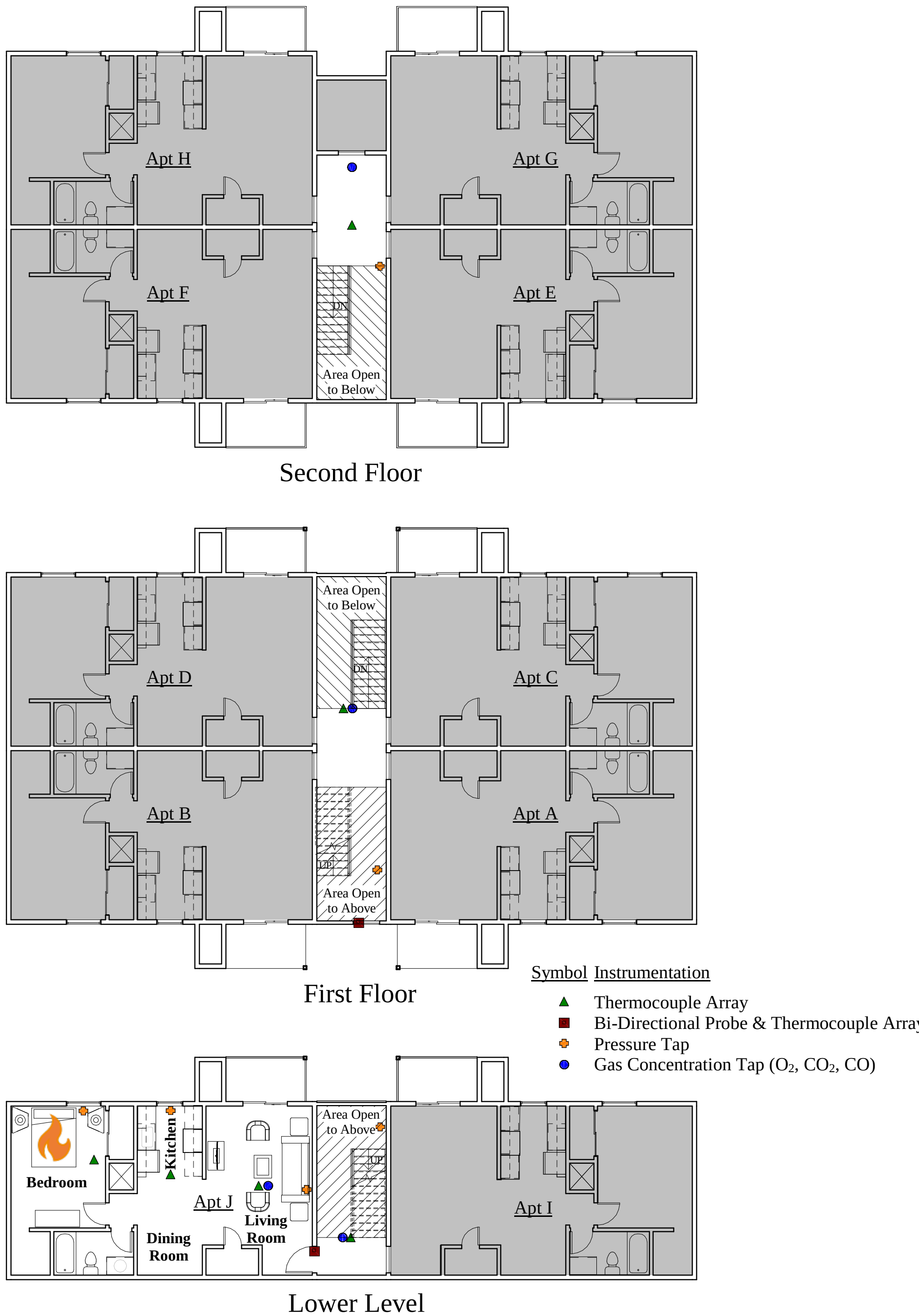


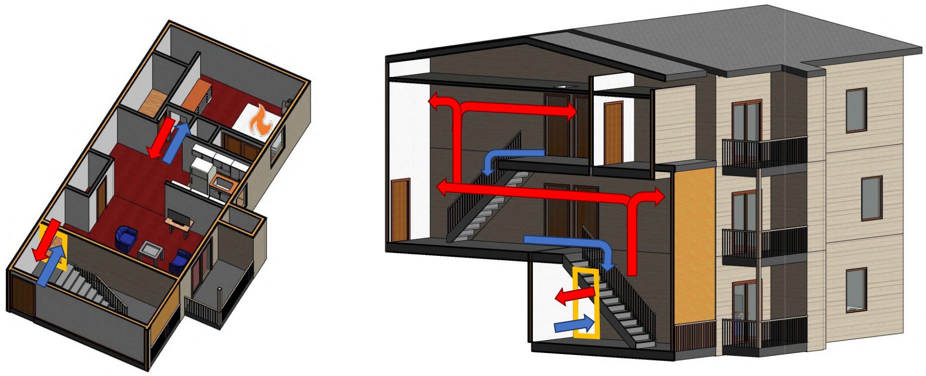
Figure 3.15: Instrumentation locations in Experiment 1B.

The bedroom, kitchen, and living room were furnished with the fuel loads described and photographed in Section 2.5.

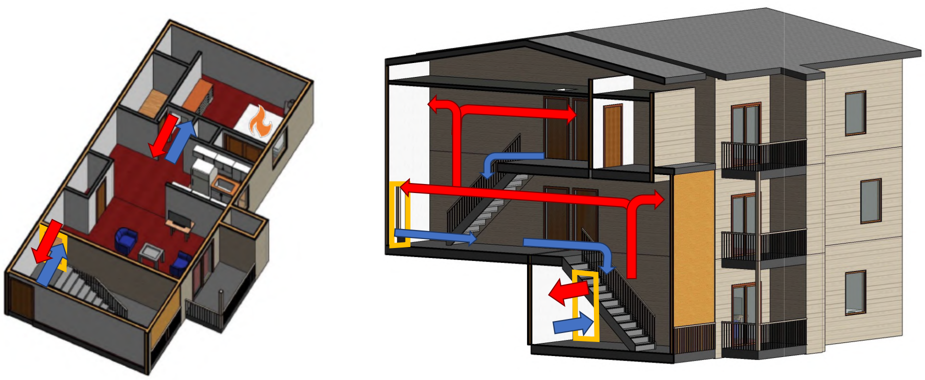
The fire in Experiment 1B was ignited in a small, plastic waste container placed next to the head of the bed (t = 0 s). Fire growth was uninhibited in the fire apartment until the oxygen available for combustion was consumed. Smoke became visible in the stairwell at about 120 s (2:00). A smoke layer formed at the top of the stairwell and had descended to the second-floor landing by 205 s (3:25). At 240 s (4:00), the smoke layer had descended to the floor of the lower level. Zero visibility conditions remained until fire department interventions occurred.

The first fire department intervention in Experiment 1B was the opening of the exterior breezeway door at 600 s (10:00) post ignition. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded downstairs to the door of the fire apartment. The suppression crew entered the fire apartment and simultaneously began flowing water at 660 s (11:00). The suppression crew used a 7/8 in. smooth bore nozzle operated in an O pattern that flowed 160 gpm from a 1 3/4 in. hoseline 200 ft in length. The suppression crew then advanced to the fire room, continuing to flow water until knock down was achieved. Additional water was applied as necessary. After suppression was complete, the fire apartment was ventilated at 976 s (16:16) by opening the bedroom window, kitchen window, and living room sliding glass door. Note: For Experiment 1B the water flow meter did not function properly and therefore water flow data was not recorded. An estimated total flow of 264 gallons for initial suppression was determined from audible flows recorded on video.

The flow of combustion gases and fresh air during Experiment 1B are sketched in Figure 3.16. As the fire grew in the bedroom, high temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the common space in the apartment (the kitchen, dining room, and living room). Entrainment from the fire plume caused air to be drawn through the bedroom doorway into the fire compartment, which continued to support combustion. As the fire continued to grow, combustion gases filled the fire apartment. The buoyant gases then spilled into the enclosed stairwell as shown in Figure 3.16a. After firefighters opened the exterior breezeway door for entry, an exhaust vent for the higher pressure gases in the enclosed stairwell was created. The gases exhausted out the top portion of the door while cool air was entrained through the bottom of the doorway (see Figure 3.16b). These flows continued until firefighters knocked down the fire on the lower-level, which stopped the production of combustion gases.



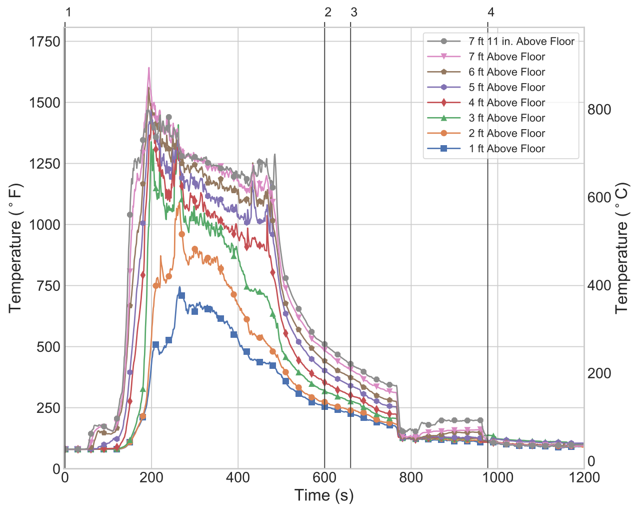
(a) Prior to Opening the Exterior Breezeway Door



(b) After Opening Exterior Breezeway Door

Figure 3.16: Changes in flow during Experiment 1B. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

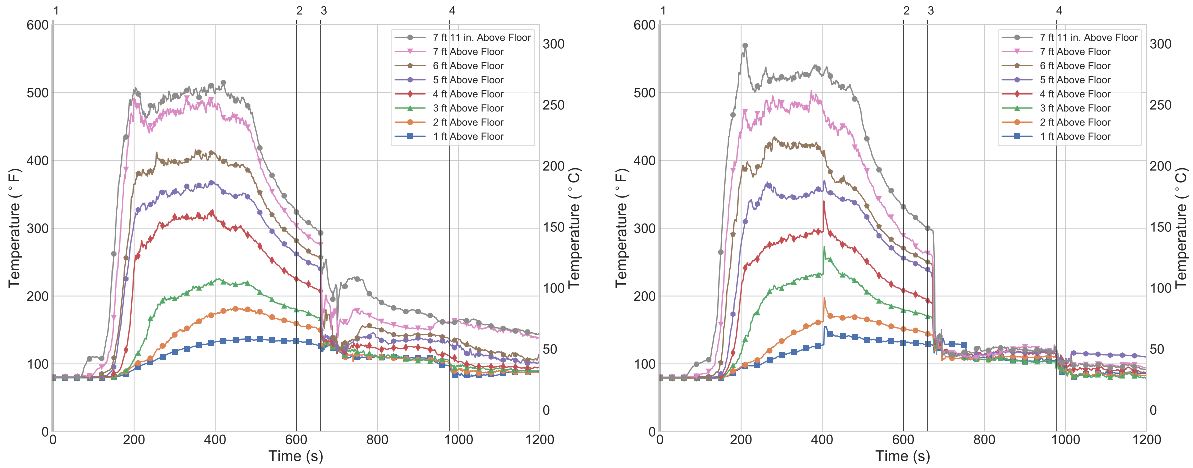
The time histories of the fire room temperatures are presented in Figure 3.17. The temperatures nearest the ceiling (6 ft and above) in the fire room increased 1 min. after ignition. Temperatures at all elevations began increasing by 140 s (2:20). At their peak (between 195 s (3:14) and 265 s (4:25)) temperatures ranged from 1650 °F 1 ft below the ceiling to 750 °F 1 ft above the floor. Temperatures in the fire room then remained steady until approximately 486 s (8:06) post ignition, at which time the temperatures began to decline. This decay prior to firefighter intervention indicates the bedroom had become ventilation-limited. When the suppression crew entered the fire apartment and began to flow water at 660 s (11:00), temperatures in the fire room were below 450 °F. A sharp decrease in the fire room temperatures occurred at 765 s (12:45), an indication the suppression crew had reached the threshold of the fire compartment.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976

Figure 3.17: Fire room (bedroom) temperatures for Experiment 1B.

The temperatures in the kitchen and living room of the fire apartment showed a similar response to those measured in the bedroom, but with lower peaks (see Figure 3.18). The temperatures in both rooms reached peaks approximately 200 s (3:20) post ignition and remained steady until approximately 480 s (8:00). During this time, the peak temperatures in the kitchen ranged between 570 °F 1 in. below the ceiling and 155 °F 1 ft above the floor, while the living room temperatures ranged between 515 °F 1 in. below the ceiling and 140 °F 1 ft above the floor. The temperature in both rooms then decreased in response to the compartment becoming ventilation-limited.



(a) Living Room (b) Kitchen

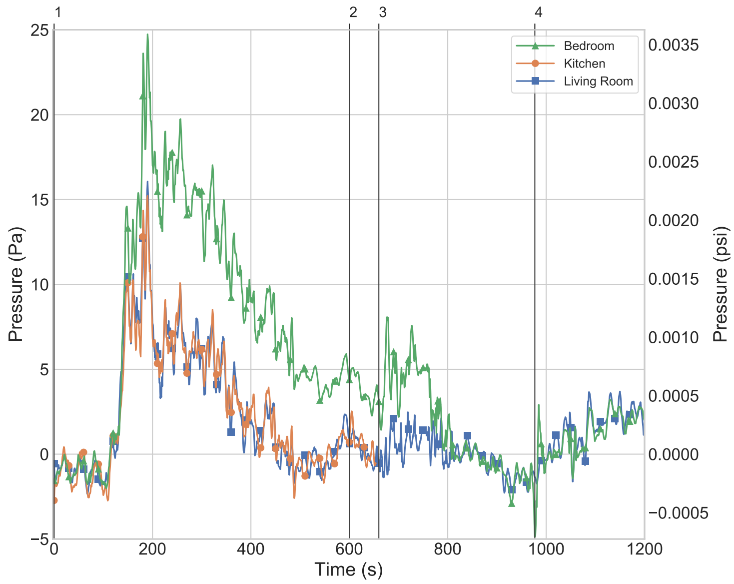
	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976

Figure 3.18: Living room and kitchen temperatures for Experiment 1B.

When the suppression crew entered the fire apartment at 660 s (11:00), temperatures at all elevations in both rooms were below 300 °F. The temperature in the living room (see Figure 3.18a) decreased immediately in response to the suppression crew starting to flow water at 660 s (11:00). Fifteen seconds later (675 s post-ignition), temperatures in the kitchen decreased (see Figure 3.18b) in response to water application as the suppression crew advanced through the apartment.

The pressure measurements in each room of the fire apartment were closely aligned, with the exception of the bedroom pressure, which was slightly higher because it was the room of origin (see Figure 3.19). Pressures in the fire apartment began to increase 120 s (2:00) after ignition and peaked at 188 s (3:08), shortly before the temperature in the apartment peaked. The pressures peaked at 25 Pa in the bedroom, 15 Pa in the kitchen, and 16 Pa in the living room. Pressures then slowly declined until reaching ambient (0 Pa), which occurred at 480 s (8:00) in both the kitchen and the living room. This time corresponded to the beginning of temperature decline in the fire apartment. The open apartment door for the duration of the experiment limited the pressure rise compared to the closed compartment of Experiment 1A.

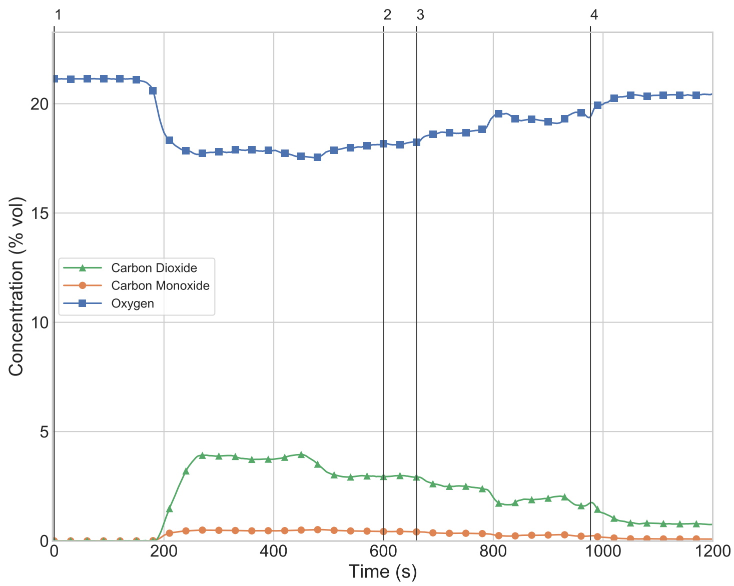
The pressure in the bedroom was 4 Pa when the suppression crew entered the fire apartment at 660 s (11:00), and it reached 0 Pa at 805 s (13:25). Pressures in the fire apartment remained near 0 Pa for the rest of the experiment. The pressure tap in the kitchen was impacted by water during suppression, so data from that sensor after suppression began (660 s (11:00)) is omitted.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976

Figure 3.19: Fire apartment pressures for Experiment 1B. Each pressure tap was installed 4 ft above the floor.

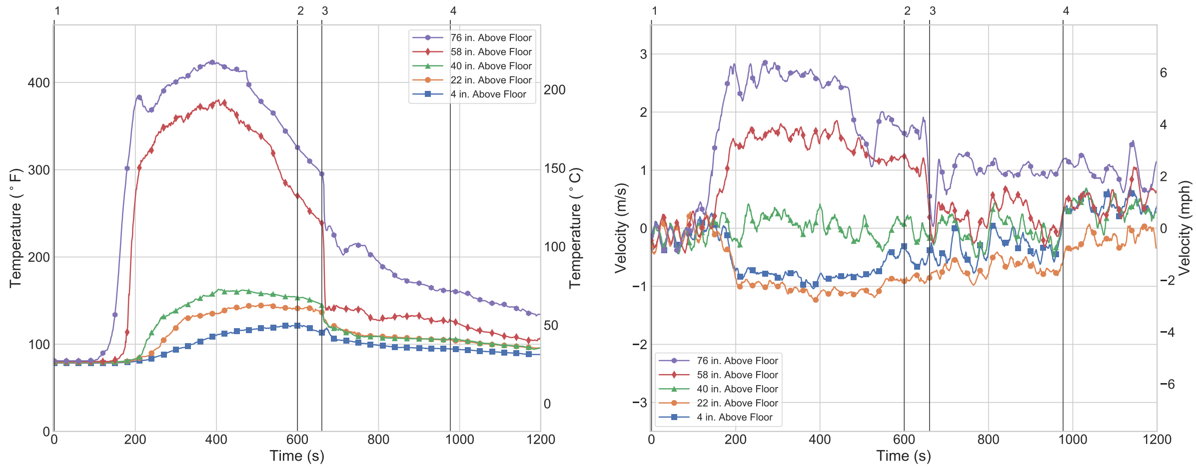
Gas concentrations were measured in the living room of the fire apartment (see Figure 3.20). Gas concentrations began to change in response to the fire growth at around 150 s (2:30). The O_2 concentration decreased to a minimum of 17.6% at 260 s (4:20). At the same time, the CO and CO_2 concentrations reached maximums of 0.5% (5000 ppm) and 4.0%, respectively. The gas concentrations remained steady until approximately 480 s (8:00), when they began slowly returning to ambient conditions. The transition from steady to improving conditions corresponded to the beginning of the fire decay stage, as indicated by the other instrumentation. Gas concentrations slowly improved for the rest of the experiment. By 976 s (16:16), when the fire apartment was ventilated, the O_2, CO, and CO_2 concentrations had reached 19.3%, 0.2% (2000 ppm), and 1.7%, respectively. The open apartment door allowed for an exchange of gases to the stairwell volume, which limited the magnitude of the gas concentration changes in the living room.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976

Figure 3.20: Living room gas concentrations for Experiment 1B. Measurement location was 4 ft above the floor.

The time histories of the gas velocities and temperatures through the fire apartment door (see Figure 3.21) corroborates the patterns of gas movement indicated by the pressure and temperature measurements discussed previously. During the peak and steady-state stages of the fire (approximately 200 s (3:20) to 480 s (4:00)), there was bi-directional flow through the fire apartment door—probes 40 in. above the floor show gases exhausting from the apartment between 1 m/s and 3 m/s (2 mph and 6 mph) at 350 °F to 425 °F. At 40 in. above the floor, the flow was negligible, an indication of the neutral plane location. Gases below 40 in. entered the apartment at approximately 1 m/s (2 mph).



(a) Temperature (b) Velocity

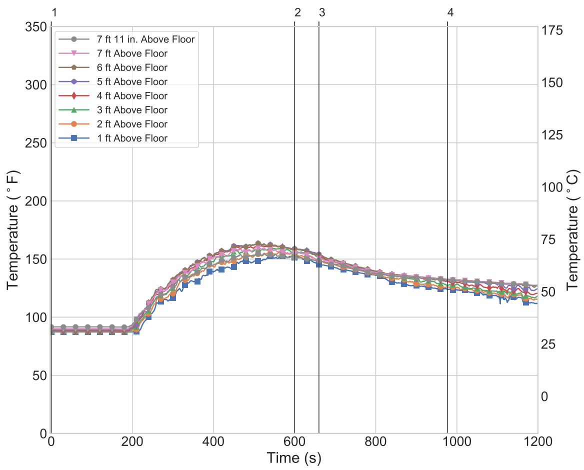
	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976

Figure 3.21: Apartment J door temperatures and velocities for Experiment 1B.

The start of suppression at 660 s (11:00) reduced the velocity and temperature of gases exiting the fire apartment door. This was because air entrainment from the flowing hoseline was able to occlude combustion gases and the production of combustion gases slowed as the fire was suppressed. During suppression, gas flow through the apartment door was steady—elevations below the 76 in. probe measured intake or near zero flow. The 76 in. elevation showed exhaust, at about 1 m/s. This high exhaust was likely due to venting gases located behind the advancing suppression crew. Venting the apartment at 976 s (16:16) reduced the intake velocity through the apartment door as fresh air entered through the open apartment vents.

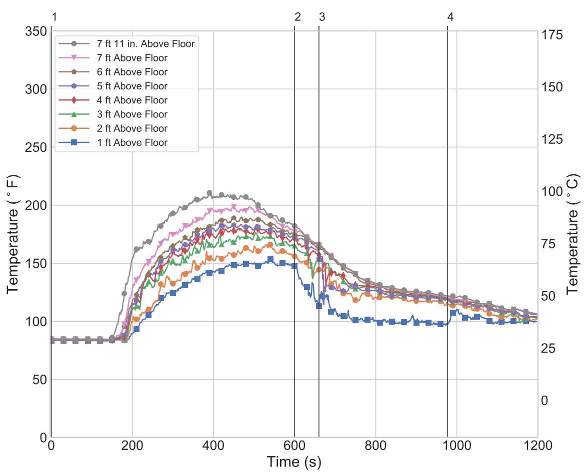
Similar to the apartment doorway, temperatures in the stairwell began to increase at about 120 s (2:00) post ignition, starting near the ceiling of the lower-level (see Figure 3.22). By 210 s (3:30), temperatures on the second-floor of the stairwell had increased. Temperatures on the lower-level were stratified throughout the experiment due to the bi-directional flow of hot gases exhausting from the top of the apartment door and air entrained through the bottom of the door. Temperatures 5 ft and lower remained below 200 °F, while temperatures 6 ft and higher reached peaks between 280 °F and 310 °F. On the first and second floors of the stairwell, the temperature profiles were relatively uniform as a result of those spaces filling completely with smoke. Peak temperatures between 1 ft above the floor and 1 in. below the ceiling were 150–165 °F on the second floor, and 155–210 °F on the first-floor.

Temperatures on each floor of the stairwell began decreasing after the fire entered the decay stage (starting around 480 s (8:00)). On the first and second floors of the stairwell, temperatures continued to decrease for the remainder of the experiment. Temperatures on the lower level of the stairwell showed a sharp decrease at 660 s (11:00) corresponding to suppression operations beginning in the fire apartment. The flow-and-move suppression controlled the flow path, preventing hot gases from continuing to enter the stairwell, and drawing cooler fresh air in from above.

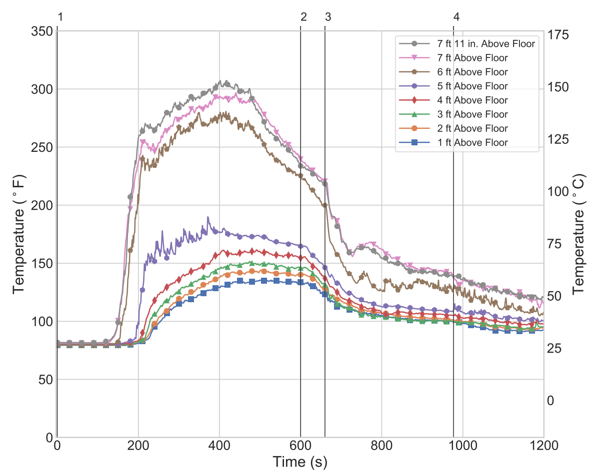


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976



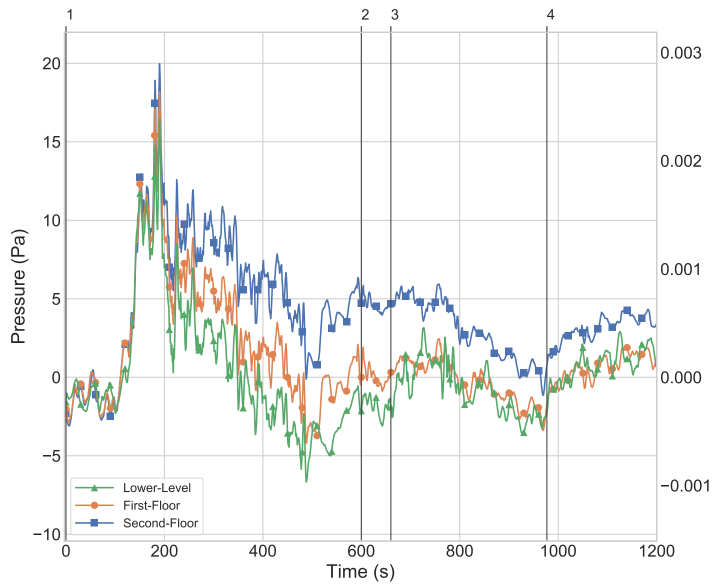
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.22: Stairwell temperatures for Experiment 1B.

The time histories of the pressures in the stairwell are shown in Figure 3.23. The stairwell pressures reflect the same growth and decay timing as the pressures measured in the fire apartment due to those spaces being connected by the open apartment door. Pressures in the stairwell began to increase 100 s (1:40) after ignition and peaked at 188 s (3:08), the same time as the fire apartment peak pressure. Pressures on the lower level, first floor, and second floor of the stairwell peaked at approximately 13 Pa, 15 Pa, and 16 Pa, respectively. Pressures on each floor then began to decrease, reaching minimums around 500 s (8:20), which corresponded to the time the fire became under-ventilated. The minimum pressures were -5 Pa, -4 Pa, and 1 Pa on the lower level, first floor, and second floor, respectively.

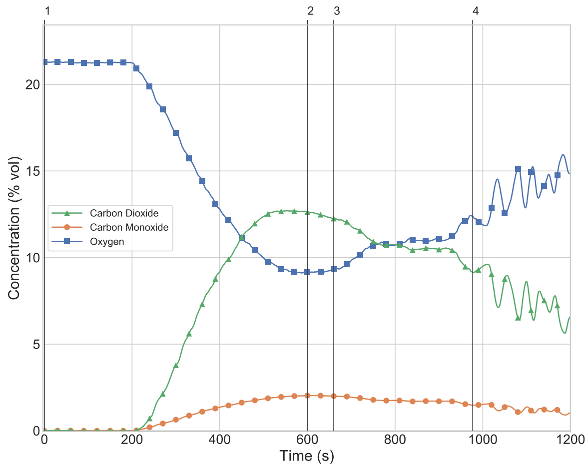


	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976

Figure 3.23: Stairwell pressures for Experiment 1B. Each pressure tap was installed 4 ft above the floor.

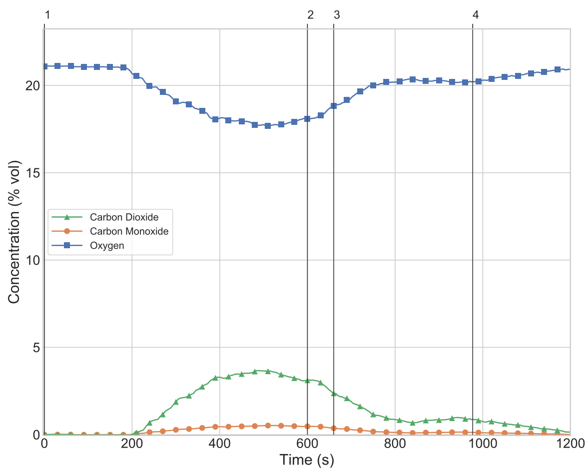
When the exterior door was opened at 600 s (10:00), smoke flowed out of the structure to an area of lower pressure. This decreased the pressure on each floor in the stairwell by approximately 1 Pa. The pressures then returned to their values prior to opening the exterior door because the fire was not yet suppressed. Pressures in the stairwell decreased from the start of suppression at 660 s (11:00) until the fire room was ventilated at 976 s (16:16). The lower-level and first-floor pressures reached negative values during this time as air was pulled from those spaces into the fire apartment to compensate for gases contracting during cooling in combination with air entrained due to suppression methods. When the fire apartment was ventilated, pressures in the stairwell equalized to ambient conditions.

The gas concentrations in the stairwell showed a larger response than in the fire apartment living room (see Figure 3.24). Gas concentrations on each floor first began to respond around 200 s (3:20) post ignition. The largest response was on the second-floor. This highlights that the buoyant smoke filled the stairwell from the top down. The O_2 concentrations on the second floor and lower level fell below 15% at 345 s (5:45) and 332 s (5:32), respectively. This occurred about 2 min. after the temperatures and pressures in the fire apartment reached their peaks. The 2 min. delay reflects the transport time for air to travel horizontally through the apartment and vertically into the stairwell. The peak values on the second floor were 9.1% O_2, 2.1% (21,000 ppm) CO, and 12.7% CO_2, at 520 s (8:40). Opening the exterior door at 600 s (10:00) released some smoke from the stairwell, raising the neutral plane of the smoke layer. In response, conditions on the lower level rapidly improved. Gas concentrations on both the first and second floors gradually returned to ambient conditions.

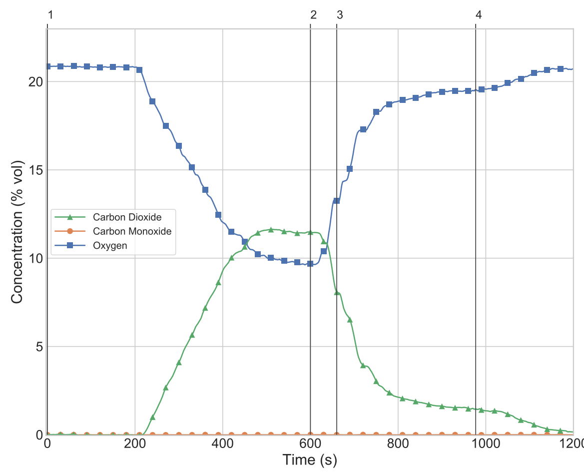


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Enter fire apartment; flow-and-move to fire room	660
4	Ventilate apartment	976



(b) First-Floor Stairwell

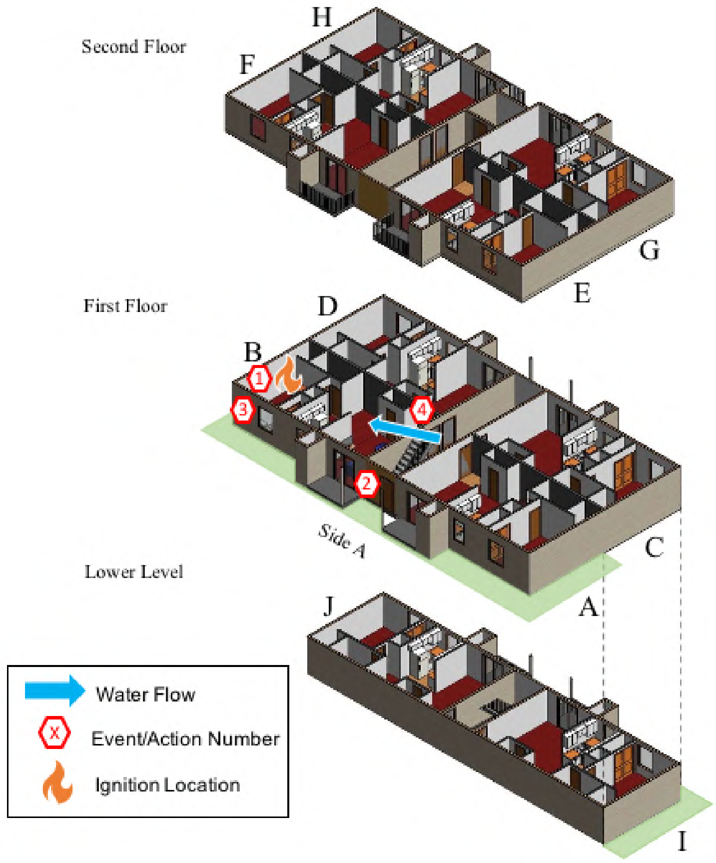


(c) Lower-Level Stairwell

Figure 3.24: Stairwell gas concentrations for Experiment 1B. Measurement locations were 4 ft above the floor.

3.3 Experiment 1C – First-Floor Apartment Fire with Coordinated Interior Suppression and Horizontal Ventilation

Experiment 1C was conducted in Apartment B of 1980 Kimberly Village Lane, and it was designed to evaluate the coordination of interior suppression with horizontal ventilation for a fire originating in the bedroom of a first-floor apartment. Prior to ignition, all exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was open for the duration of the experiment. There was minimal smoke and no fire showing on the exterior of the structure at the start of firefighter intervention. Firefighter intervention included venting the bedroom (fire room) window concurrently with entry to the structure, followed by entry into the fire apartment and flow-and-move suppression into the fire compartment. Figure 3.25 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Open exterior door	03:17	197
3	Ventilate bedroom window	03:33	213
4	Open apartment door; flow-and-move to fire room	03:40	220

Figure 3.25: Time and sequence of actions and events for Experiment 1C.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.26 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

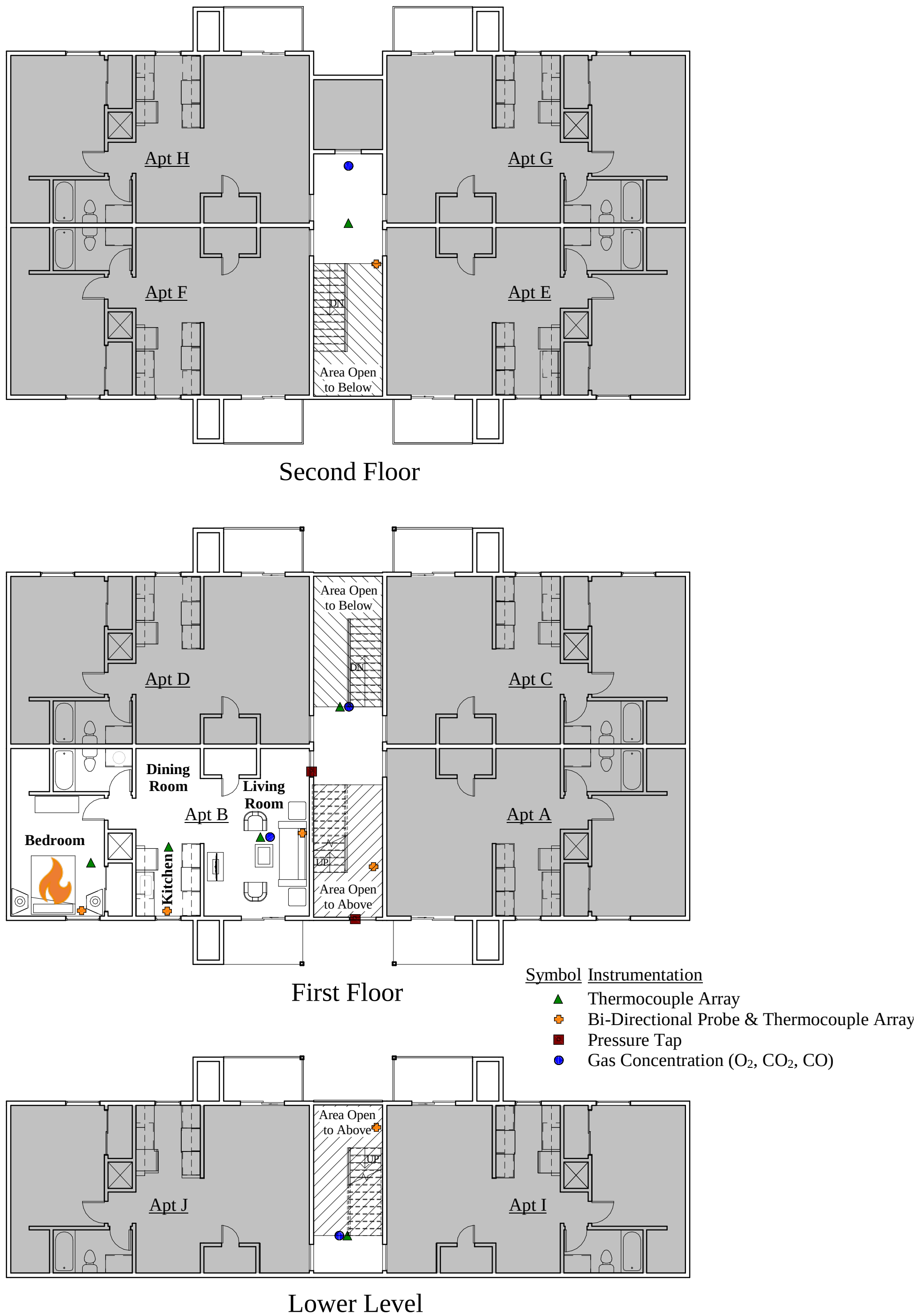


Figure 3.26: Instrumentation locations in Experiment 1C.

The bedroom, kitchen, and living room were furnished with the fuel loads described and photographed in Section 2.5.

The fire in Experiment 1C was ignited in a small, plastic waste container placed next to the head of the bed (t = 0 s). Fire growth was uninhibited in the fire apartment until the oxygen available for combustion was consumed. As the smoke layer in the fire room began to build and descend, the cameras in the fire apartment became obscured, and they were completely dark by approximately 213 s (3:33). Zero visibility conditions remained until fire department interventions occurred. Only minimal smoke was visible in the stairwell through normal leakage around the closed apartment door.

Fire department intervention began after fire room temperatures peaked and began to decrease. This behavior indicated the fire began to decay because of a lack of available oxygen for combustion in the apartment. The first fire department intervention was the opening of the exterior breezeway door at 197 s (3:17) post ignition. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. One second after entry to the stairwell (213 s (3:33)), a separate crew broke the bedroom (fire room) window to provide horizontal ventilation. Figure 3.27 shows images of the fire room from the exterior immediately before, immediately after, and 20 s after venting the fire room window. Flames extended out the bedroom window upon ventilation, as shown in Figure 3.27b. At 220 s (3:40)—7 s after the bedroom window was opened—the suppression crew opened the apartment door, and within 5 s of the open door began flowing water at 160 gpm from a 7/8 in. smooth bore nozzle attached to 200 ft of 1 3/4 in. hoseline, and advanced to the bedroom (fire room) while flowing. The nozzle was operated in an O pattern. The nozzle was open for a total of 38 s and flowed 97 gallons of water. Note: This value does not include the additional water used during overhaul operations. The initial interior suppression operation knocked down the fire.

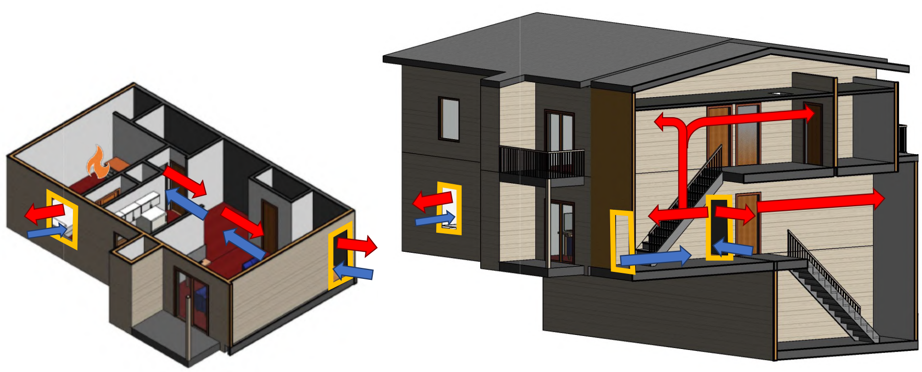
(a) Immediately before Ventilation | (b) Immediately after Ventilation | (c) 20 s after Ventilation; During Interior Suppression

Figure 3.27: Images of the fire room (bedroom) window in Experiment 1C being broken to provide horizontal ventilation in coordination with interior suppression.

The flows of combustion gases and fresh air during Experiment 1C are sketched in Figure 3.28. As the fire grew in the bedroom, high-temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the common space in the apartment (the kitchen, dining room, and living room). Entrainment from the fire plume caused air to be drawn through the bedroom doorway into the fire compartment, which led to further fire growth (see Figure 3.28a) and combustion gases to fill the fire apartment. Just prior to firefighters breaking the bedroom (fire room) window, the suppression crew opened the exterior breezeway door. The open window created a low-pressure exhaust for the higher pressure gases (see Figure 3.28b). Combustion gases exhausted out the top portion of the window while cooler, ambient air was entrained low. Firefighters opened the apartment door to begin suppression 5 s later. The open apartment door was a second low-pressure vent and a more efficient intake because it lacked a sill. The open door led to combustion gas flow into the enclosed stairwell through the top of the doorway as cooler, ambient air was entrained through the lower portion (see Figure 3.28c). Additionally, as a result of the open door, the fire room window became a more efficient exhaust vent. The suppression crew extinguished the fire, which stopped the production of combustion gases.

(a) Prior to Opening the Exterior Breezeway Door

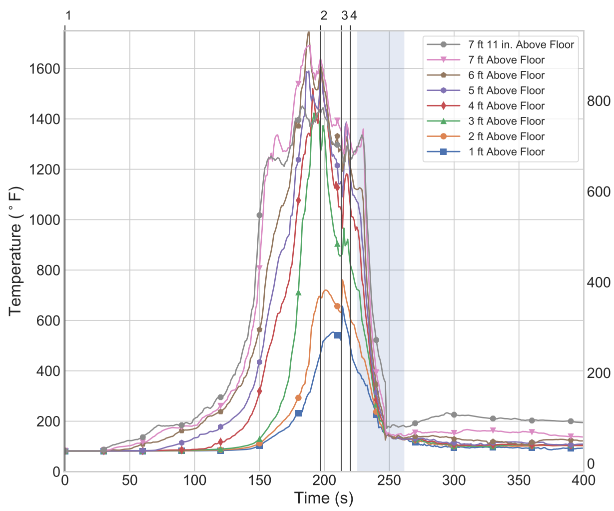
(b) After Opening the Breezeway Door and Venting the Bedroom Window



(c) After Opening the Fire Apartment Door

Figure 3.28: Changes in flow during Experiment 1C. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

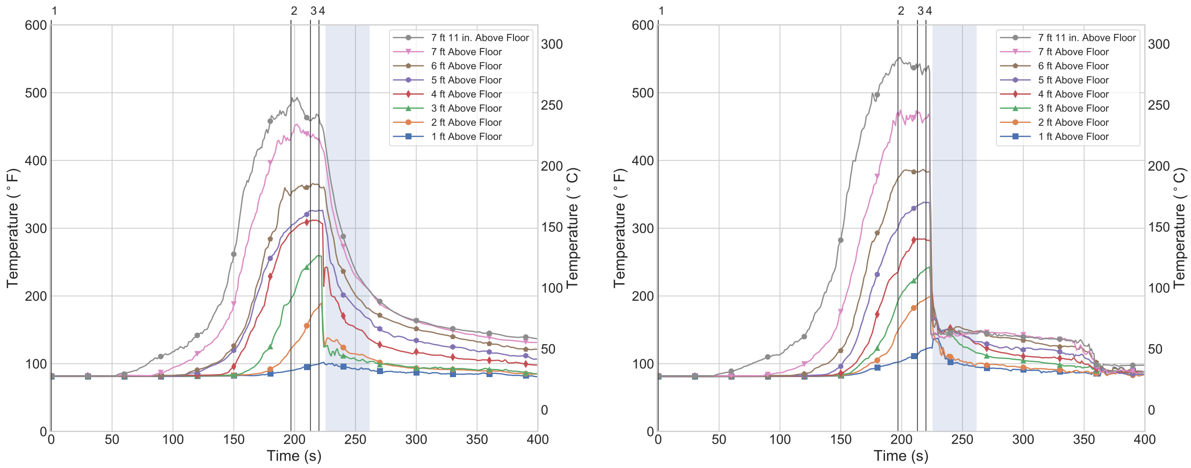
The time histories of the fire room temperatures are presented in Figure 3.29. Temperatures near the bedroom ceiling began to increase 30 s post ignition. Temperatures at all elevations began increasing by 140 s (2:20). At their peak (between 183 s (3:03) and 207 s (3:27)) the temperatures were stratified: Peak temperatures above 2 ft ranged between 1425 °F and 1750 °F, while temperatures at 1 ft and 2 ft did not exceed 800 °F. After reaching a peak, temperatures in the fire room began to decrease, an indication the compartment became ventilation-limited. When the bedroom window was opened at 213 s (3:33), flames immediately extended out of the top of the window and fresh air entered through the bottom of the window. Temperatures at all elevations in the bedroom experienced a short spike of more than 100 °F as the fire grew in response to ventilation. The cool air that entered the room briefly cooled temperatures at 6 ft and below. Interior suppression began 10 s after the window was vented, which led to a subsequent and final decrease in bedroom temperatures.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

Figure 3.29: Fire room (bedroom) temperatures for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

The temperatures in the kitchen and living room of the fire apartment reflected the growth of the fire and subsequent suppression (see Figure 3.30). Temperatures near the ceiling in both rooms began increasing at 50 s post ignition. The peak temperature in the kitchen (550 °F) was slightly higher than in the living room (495 °F) due to the proximity to the fire room. The peak temperatures were measured 1 in. below the ceiling and occurred between 199 s (3:19) and 202 s (3:22)—prior to suppression at 225 s (3:45). Temperatures in the kitchen responded immediately to suppression, dropping below 200 °F at all elevations. Temperatures in the living room responded slightly slower, with temperatures at all elevations falling below 200 °F by 266 s (4:26)—41 s after suppression started.



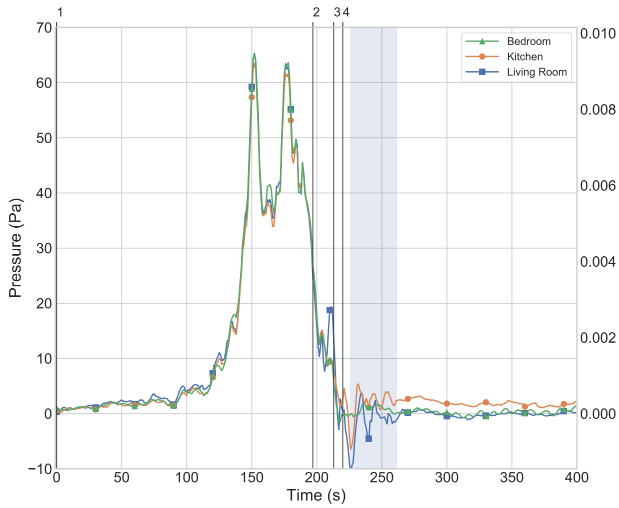
(a) Living Room

(b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

Figure 3.30: Living room and kitchen temperatures for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

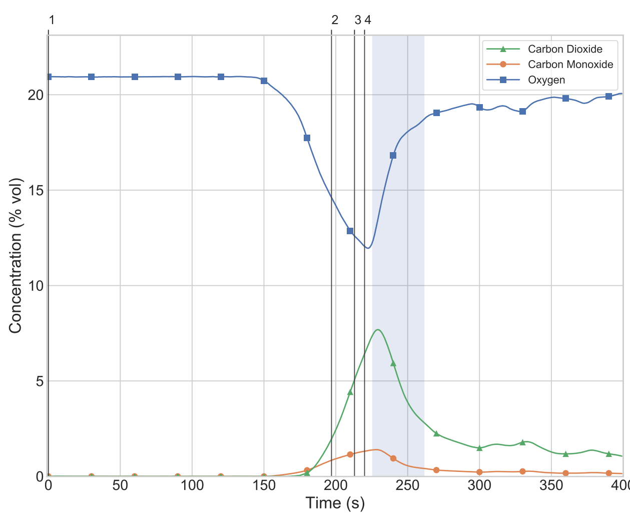
The pressure measurements in each room of the fire apartment were closely aligned (see Figure 3.31). There were two peaks in the fire apartment pressures during the fire growth stage. The first peak was at 152 s (2:32) and was about 65 Pa in each room of the fire apartment. The second peak was at 180 s (3:00) and was about 63 Pa in each room of the fire apartment. After the second peak, pressures in the fire apartment decreased to below 0 Pa by 224 s (3:44), immediately prior to the start of suppression at 225 s (3:45). The drop in pressure prior to suppression indicates the fire became ventilation-limited. The pressures in the fire apartment remained at approximately ambient conditions after suppression started.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

Figure 3.31: Fire apartment pressures for Experiment 1C. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

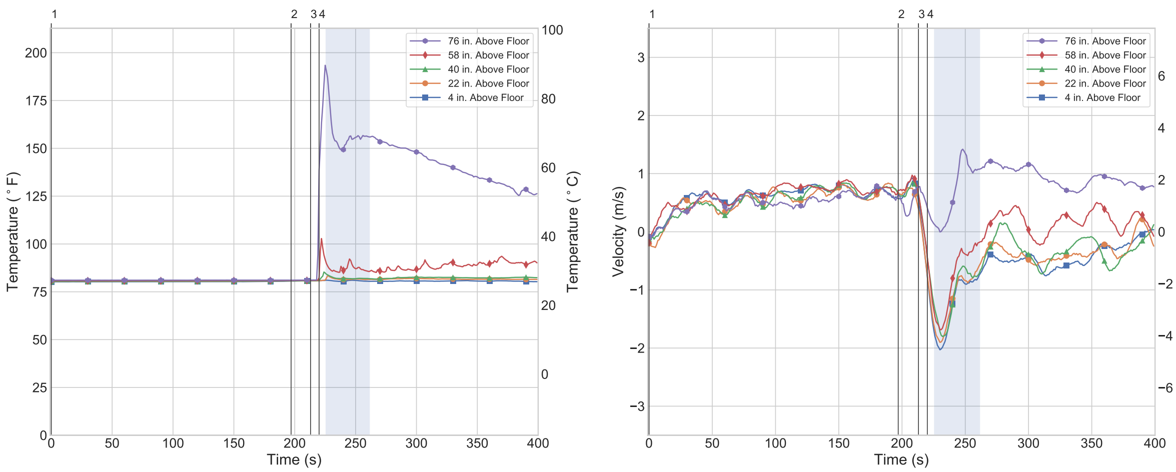
Gas concentrations were measured in the living room of the fire apartment (see Figure 3.32). Gas concentrations began to change in response to the fire growth at around 145 s (2:25). At 194 s (3:14), the O_2 concentration fell below 15%, which coincided with the peak temperatures and pressures in the fire apartment as the fire transitioned to a ventilation-limited state. At oxygen levels between 13% to 15%, flames will begin to self-extinguish [29, 30], and in this fire the O_2 concentration decreased to a minimum of 12.0% at 222 s (3:42). Shortly after at 230 s (3:50), the CO and CO_2 concentrations reached maximums of 1.4% (14,000 ppm) and 7.7%, respectively. These peak values occurred just prior to the start of suppression at 225 s (3:45). The knock down of the fire and ventilation via the bedroom window and apartment door led the gas concentrations in the apartment to return to ambient conditions.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

Figure 3.32: Living room gas concentrations for Experiment 1C. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened 220 s post ignition, which allowed the combustion gases in the fire apartment to flow into the stairwell. Figure 3.33 shows the temperatures and velocities recorded at the fire apartment door. After the suppression crew opened the apartment door, combustion gases at 76 in. above the floor flowed into the stairwell at greater 175 °F at approximately 1 m/s (2 mph). At the 58 in. elevation and below, flow was initially into the apartment as the vent in the fire room acted as an exhaust vent for the higher pressure fire room gases. Following suppression, gas flow out of the door slowed toward 0 m/s because the production of combustion gases had stopped. The thermocouple at the 58 in. elevation did measure an increase in temperature despite the inflow due to heat transfer from the hot gases exhausting through the doorway above the probe.



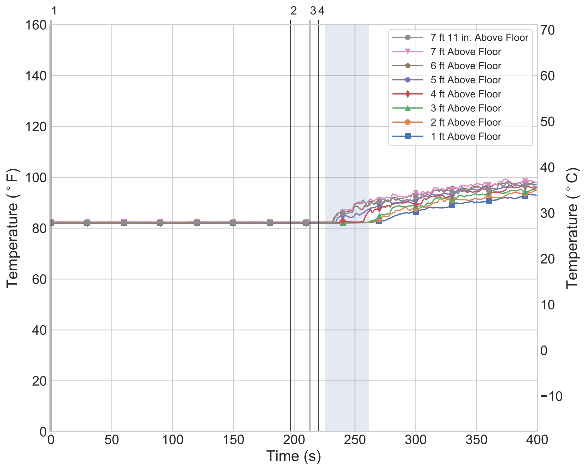
(a) Temperature

(b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

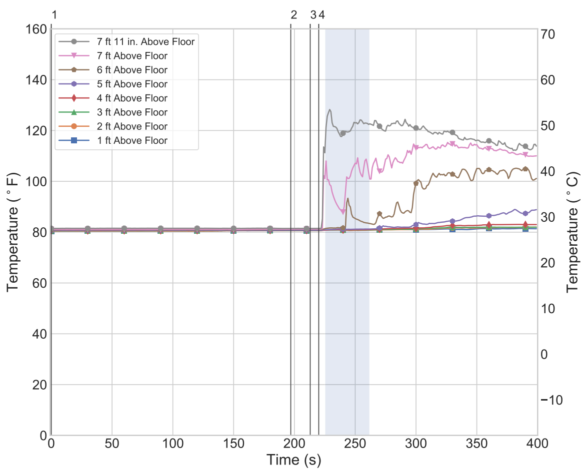
Figure 3.33: Apartment B door temperatures and velocities for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

The temperatures measured on each floor of the stairwell remained ambient and steady (about 85 °F) until the fire apartment door was opened (see Figure 3.34). After the apartment door was opened, temperatures on the first and second floors increased as smoke from the previously closed fire apartment door began to fill the stairwell. On the second-floor, temperatures at all elevations rose to between 90 °F and 100 °F. On the first floor, temperatures measured 6 ft above the floor and higher showed a sharp spike corresponding with the opening of the apartment door—the highest spike was 130 °F measured 1 in. below the ceiling. Thermocouples below 3 ft on the first floor and at all elevations on the lower level of the stairwell did not measure an increase in temperature because the smoke layer stayed above the 3 ft level on the first floor.

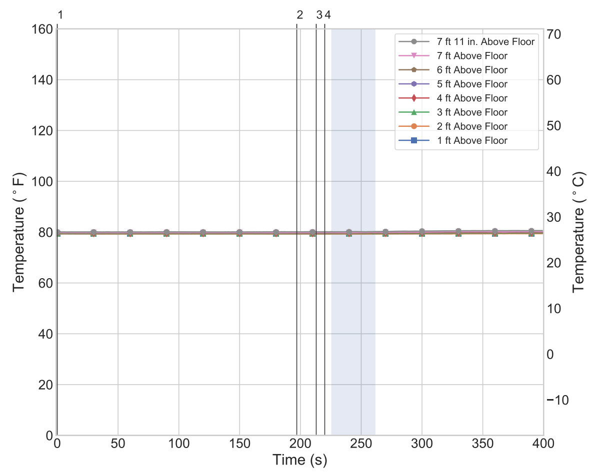


	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

(a) Second-Floor Stairwell



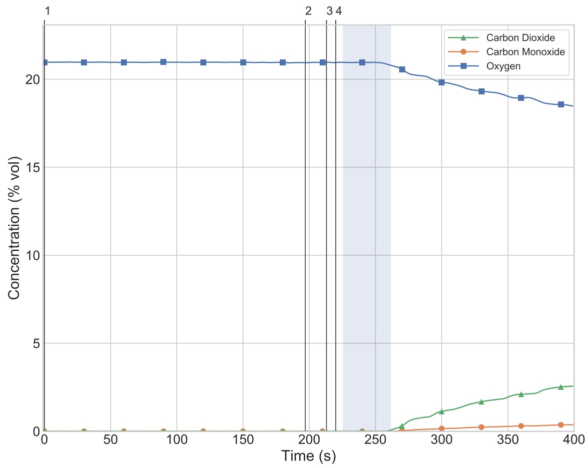
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

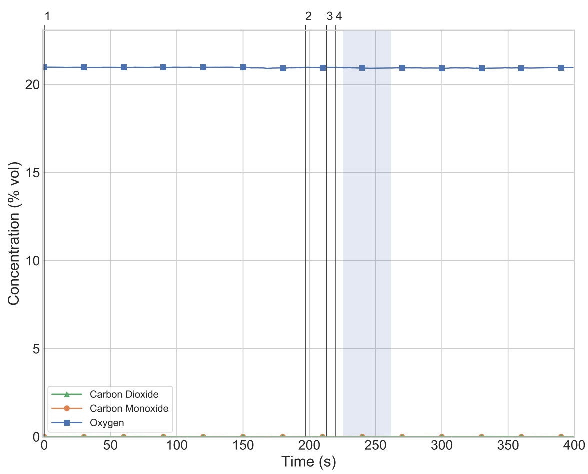
Figure 3.34: Stairwell temperatures for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

Similar to Experiment 1A in which the fire apartment door was closed until suppression actions began, the stairwell pressure in Experiment 1C did not show a measurable increase in stairwell pressure (see Figure 3.35). Gas concentrations on the lower level and first floor of the stairwell reflected ambient conditions throughout the experiment because the smoke layer did not descend to the elevation of the measurement locations. Gas concentrations on the second floor of the stairwell began to change at approximately 250 s (4:10), 25 s after the fire apartment door was opened. By about 460 s (7:40), the second-floor O_2 concentration decreased to a minimum of 18%, and CO_2 and CO concentrations increased to maximums of 3.1% and 0.5% (5000 ppm), respectively.

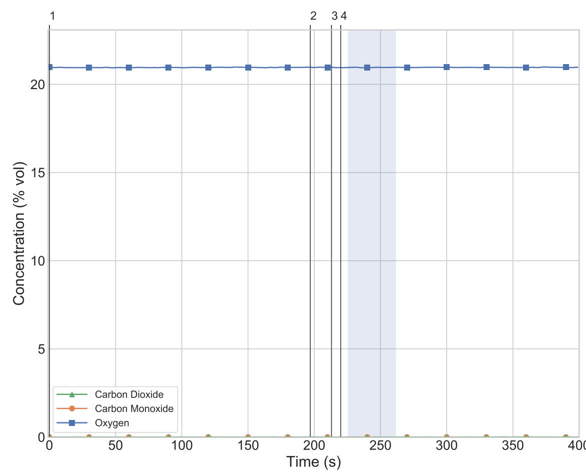


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220



(b) First-Floor Stairwell

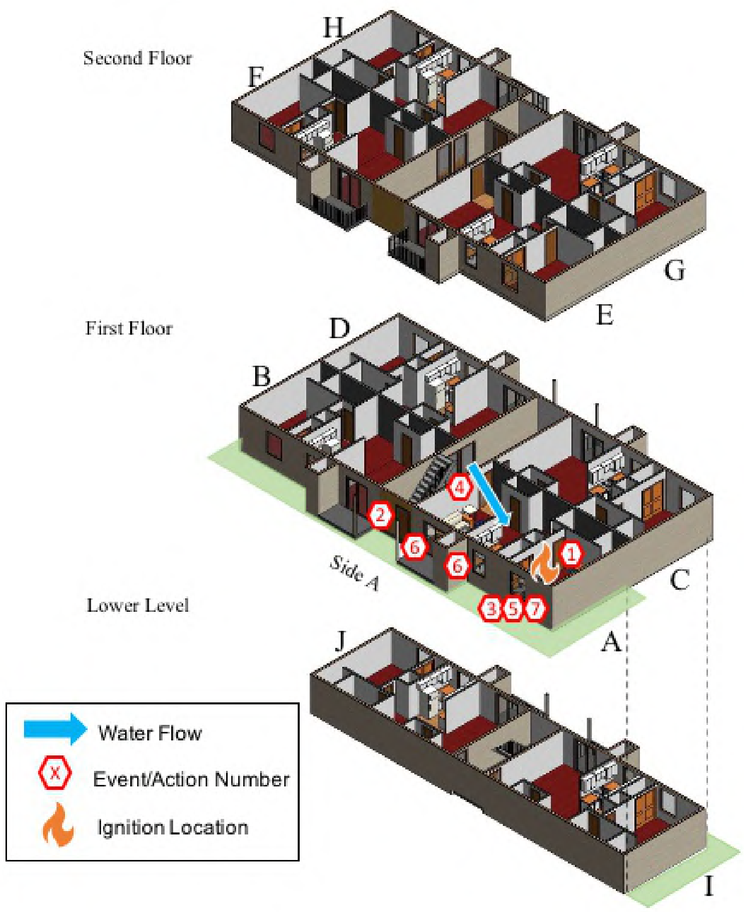


(c) Lower-Level Stairwell

Figure 3.35: Stairwell gas concentrations for Experiment 1C. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

3.4 Experiment 1D – First-Floor Apartment Fire with Coordinated Interior Suppression, Horizontal Ventilation, Door Control and Hydraulic Ventilation

Experiment 1D was conducted in Apartment A of 1980 Kimberly Village Lane, and it involved the same scenario as Experiment 1C—coordination of interior suppression with horizontal ventilation—but with the addition of door control at the fire apartment entrance and hydraulic ventilation post knock down. The fire originated in the bedroom of a first-floor apartment without ventilation. Prior to ignition, all exterior windows and doors were closed, including thefire apartment door and doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was open for the duration of the experiment. There was minimal smoke and no fire showing on the exterior of the structure at the start of firefighter intervention. Firefighter intervention included venting the bedroom (fire room) window concurrently with entry to the structure, followed by entry into the fire apartment and flow-and-move suppression into the fire compartment. The door to the fire apartment was controlled during suppression. Hydraulic ventilation was used after initial knock down to remove smoke from the structure. Figure 3.36 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Open exterior door	03:33	213
3	Vent bedroom window	03:48	228
4	Open apartment door (door controlled); flow-and-move to fire room	03:57	237
5	Begin hydraulic ventilation	05:12	312
6	Ventilate kitchen and living room	07:12	432
7	End hydraulic ventilation	08:13	493

Figure 3.36: Time and sequence of actions and events for Experiment 1D.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.37 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

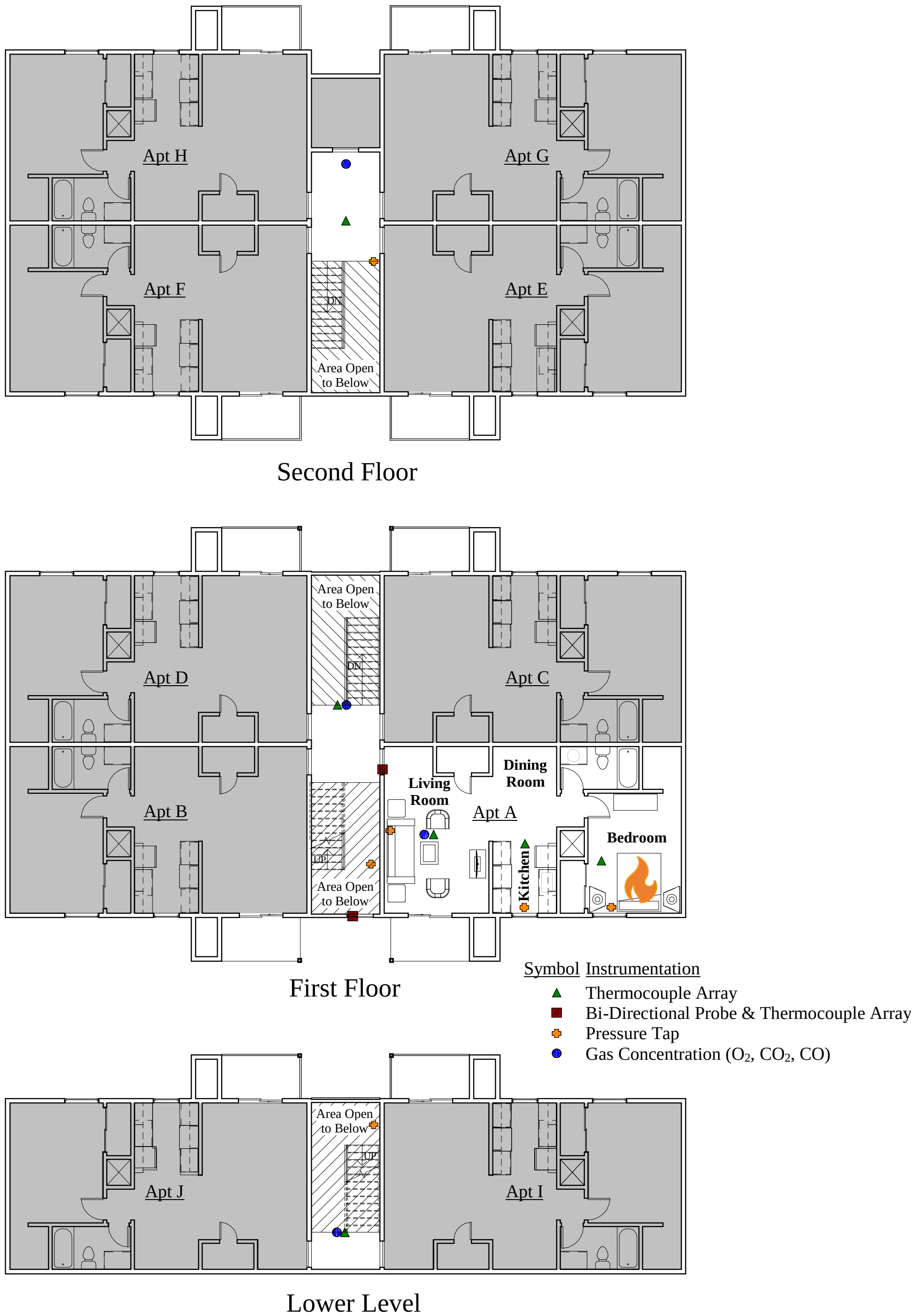


Figure 3.37: Instrumentation locations in Experiment 1D.

The bedroom, kitchen, and living room were furnished with the fuel loads described and photographed in Section 2.5.

The fire in Experiment 1D was ignited in a small, plastic waste container placed next to the head of the bed (t = 0 s). Fire growth was uninhibited in the fire apartment until the oxygen available for combustion was consumed. As the smoke layer in the fire apartment began to build and descend, the cameras in the fire apartment became obscured, and they were completely dark by around 240 s (4:00). Zero visibility conditions remained until fire department interventions occurred. Only minimal smoke was visible in the stairwell through normal leakage around the closed apartment door due to increased pressure in the fire compartment.

The first fire department intervention was the opening of the exterior breezeway door at 213 s (3:33) post ignition after the fire room temperatures had peaked. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. At the same time as the suppression crew made entry (228 s (3:48)), a separate crew broke the bedroom (fire room) window to provide horizontal ventilation. Figure 3.38 shows photographs of the fire room from the exterior immediately before and after venting the fire room window. Flames immediately began to extend out the bedroom window, as shown in Figure 3.38b.

(a) Immediately before Ventilation

(b) Immediately after Ventilation

(c) 20 s after Ventilation; During Interior Suppression

(d) 30 s after Ventilation; During Interior Suppression

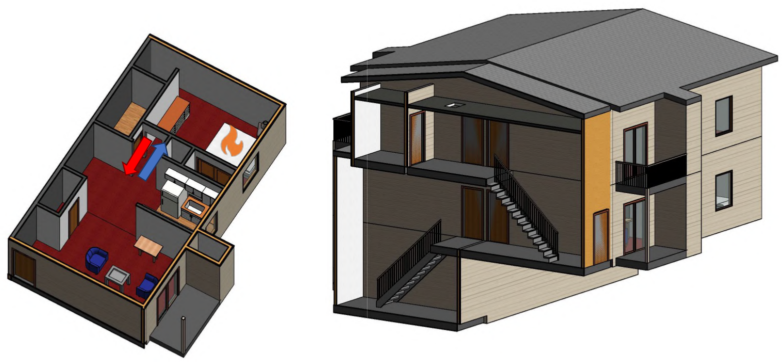
Figure 3.38: Images of the fire room (bedroom) window in Experiment 1D being broken to provide horizontal ventilation in coordination with interior suppression.

At 237 s (3:57), 9 s after the bedroom window was opened, the suppression crew opened the apartment door, began flowing water from a 150 gpm combination nozzle attached to 200 ft of 1 3/4 in.

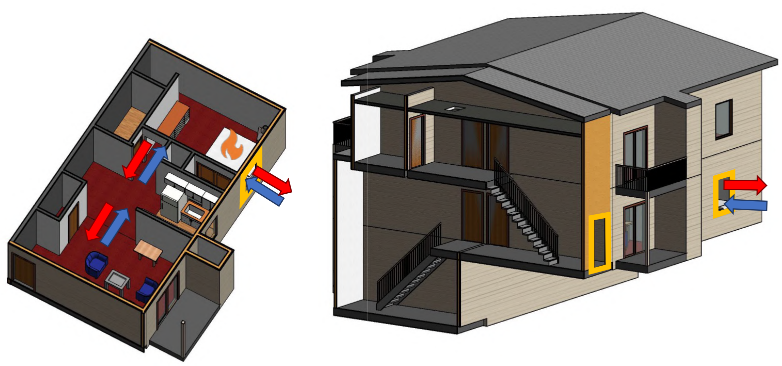
hoseline, and advanced to the bedroom (fire room) while continuing to flow. One firefighter remained at the apartment door to perform door control (i.e., the firefighter kept door closed as far as allowed by the hoseline). The hoseline was open in a straight stream, utilizing an O pattern, for a total of 50 s and flowed 115 gallons of water in the initial interior suppression operation, which successfully knocked down the fire. At 312 s (5:12), the door-control firefighter opened the door as the suppression crew began hydraulic ventilation out the bedroom window using a narrow fog pattern. Hydraulic ventilation continued until 493 s (8:13), for a total of 181 s (3:01) and 483 gallons of water. Figure 3.39 shows an image of hydraulic ventilation in progress. During hydraulic ventilation, the kitchen window and living room sliding glass door were opened at 432 s (7:12) to provide additional ventilation in the fire apartment.

Figure 3.39: Image of hydraulic ventilation from the bedroom (fire room) window in Experiment 1D.

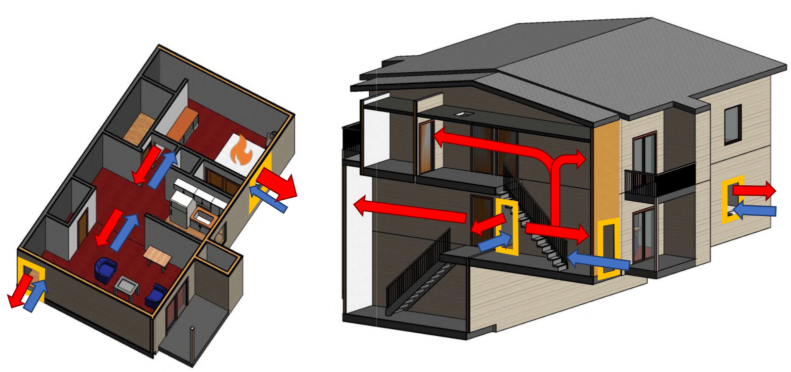
The flow paths of combustion gases and fresh air during the experiment are sketched in Figures 3.40—3.41. As the fire grew in the bedroom, high-temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the common space in the apartment (the kitchen, dining room, and living room). Entrainment from the fire plume caused air to be drawn through the bedroom doorway into the fire compartment, which led to further fire growth (see Figure 3.40a). As the fire continued to grow, combustion gases filled the fire apartment and the fire consumed the available oxygen. The suppression crew opened the exterior breezeway door just before other firefighters vented the bedroom (fire room) window, which provided a new exhaust for the higher pressure gases (see Figure 3.40b). The gases exhausted out the top portion of the window while cooler, ambient air was entrained low. About 10 s later, firefighters opened the apartment door and began suppression. The combustion gases flowed into the enclosed stairwell through the top of the door as cooler, ambient air was entrained through the lower portion (see Figure 3.40c).



(a) Prior to Opening the Exterior Breezeway Door



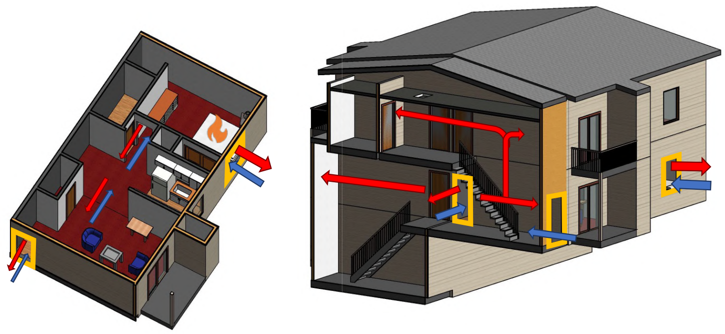
(b) After Opening the Breezeway Door and Venting the Bedroom Window



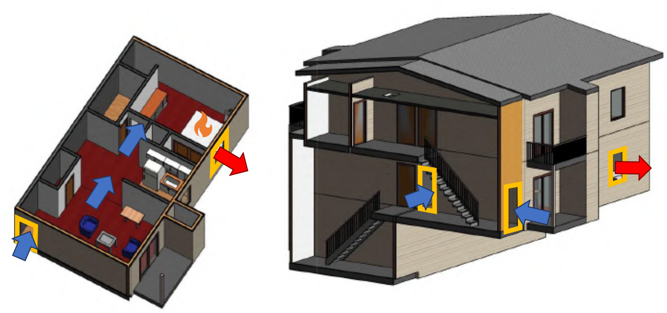
(c) After Opening the Fire Apartment Door

Figure 3.40: Changes in flow during Experiment 1D pre-knock down. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

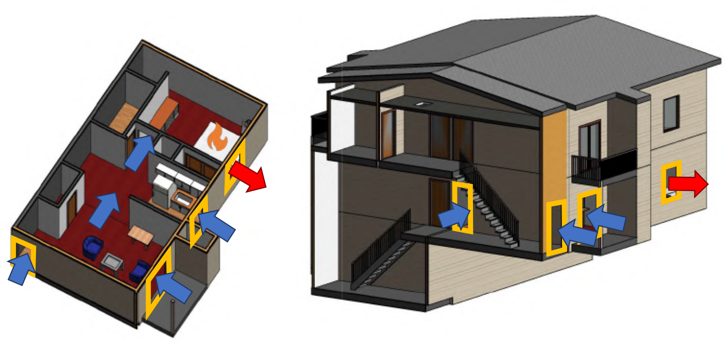
Door control was initiated, which limited the exhaust of buoyant gases and the entrainment of fresh air at the apartment door (see the change in the thickness of arrows in the stairwell in Figure 3.41a). Firefighters knocked down the fire, which stopped the production of gases, and then began hydraulic ventilation. Air entrainment from the water flow exhausted gases out the bedroom (fire room) window while fresh air flowed through the structure from the exterior breezeway door (see Figure 3.41b). Fire gases that had previously accumulated in the stairwell and fire apartment were also entrained, clearing those spaces. Ventilating the kitchen and living room two minutes later provided additional inlets for fresh air to replace the gases exhausted by hydraulic ventilation (see Figure 3.41c).



(a) After Initiation of Door Control



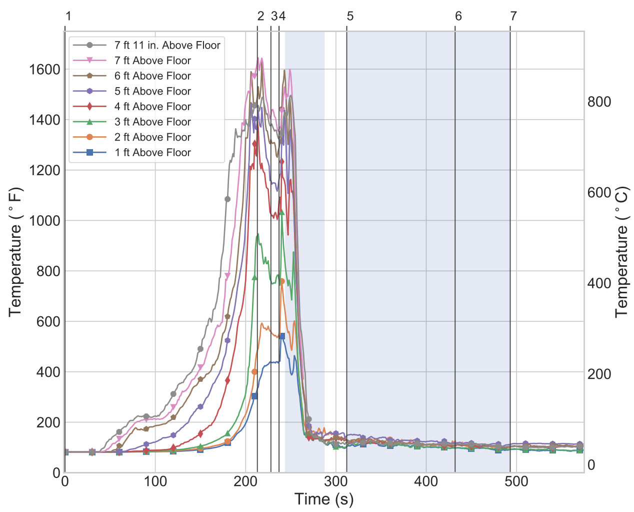
(b) After the Start of Hydraulic Ventilation



(c) After Ventilating the Kitchen and Living Room

Figure 3.41: Changes in flow during Experiment 1D following door control and hydraulic ventilation. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

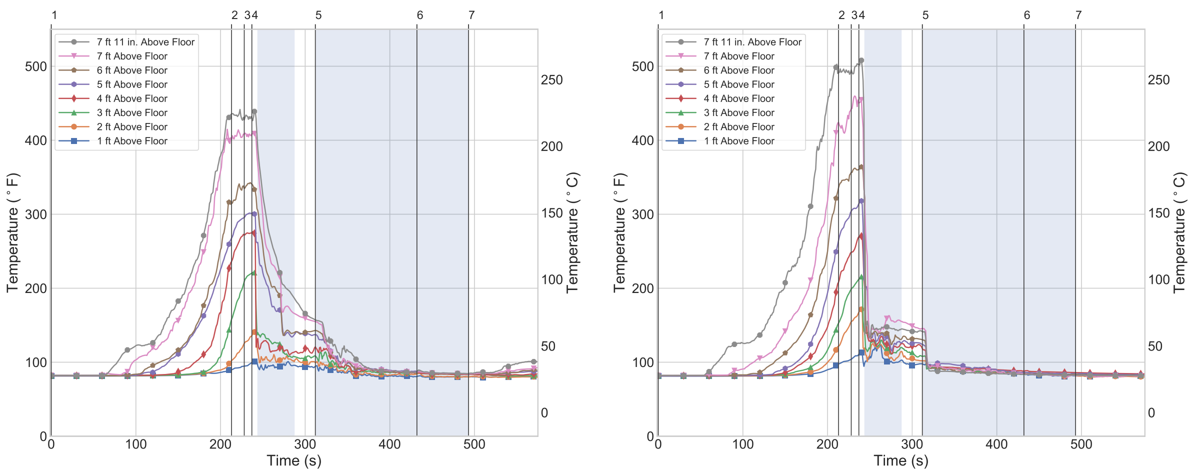
The time histories of the fire room temperatures are presented in Figure 3.42. Temperatures near the bedroom ceiling began to increase 40 s post ignition. At their peak, between 218 s (3:38) and 237 s (3:57), the temperatures were 1650 °F 7 ft above the floor and 440 °F 1 ft above the floor. After reaching their peak, temperatures in the fire room began to decrease (an indication the compartment was becoming ventilation-limited) at which point the window was broken through fire department intervention. For the 9 s between the opening of the bedroom window at 228 s (3:42) and the suppression crew entering the apartment at 237 s (3:57), bedroom temperatures remained relatively steady. Upon opening the apartment door, however, temperatures at all elevations in the bedroom increased by more than 100 °F. This temperature spike was followed by a subsequent drop in temperature as the suppression crew reached the bedroom. Temperatures at all elevations dropped below 200 °F by 270 s (4:30), 33 s after suppression started. Temperatures in the bedroom then continued to decrease toward ambient conditions for the remainder of the experiment.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

Figure 3.42: Fire room (bedroom) temperatures for Experiment 1D. Blue shaded regions indicate time and duration of water flow.

The temperatures in the kitchen and living room of the fire apartment reflect the growth of the fire and subsequent suppression (see Figure 3.43). Temperatures near the ceiling in both rooms increased at 60 s after ignition. The peak temperatures in both rooms occurred at 240 s (4:00) at 1 in. below the ceiling, and were 510 °F in the kitchen and 440 °F in the living room. The peak temperatures occurred 3 s after the apartment door was opened as the crew began to flow water at 237 s (3:57). Temperatures in the kitchen responded immediately to suppression and dropped below 200 °F at all elevations. Temperatures in the living room responded slightly slower, with temperatures at all elevations falling below 200 °F by 277 s (4:37), 40 s after suppression started.



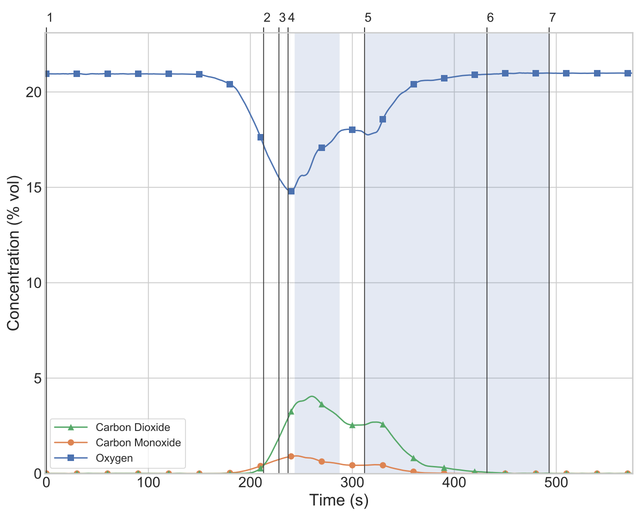
(a) Living Room (b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

Figure 3.43: Living room and kitchen temperatures for Experiment 1D. Blue shaded regions indicate time and duration of water flow.

The start of hydraulic ventilation at 312 s (5:12) increased the rate at which temperatures in the kitchen and living room decreased. The effect was faster in the kitchen due to its proximity to the vent. Prior to hydraulic ventilation, the temperatures 1 in. from the ceiling were 145 °F in the kitchen and 160 °F in the living room. Those temperatures dropped below 100 °F within 6 s in the kitchen and 51 s in the living room. Temperatures in both rooms continued to decrease for the remainder of hydraulic ventilation. In the living room, temperatures near the ceiling recovered slightly after hydraulic ventilation stopped, reaching 100 °F at 552 s (9:12), then returned to ambient conditions.

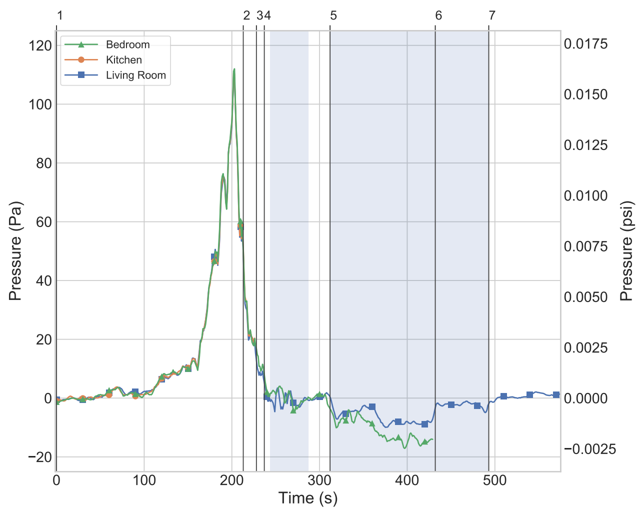
Gas concentrations were measured in the living room of the fire apartment (see Figure 3.44). Gas concentrations began to change in response to the fire growth at around 150 s (2:30). The O_2 concentration decreased to a minimum of 14.8% at 240 s (4:00). At the same time, the CO concentration reached a maximum of 1.0% (10,000 ppm). The CO_2 concentration reached a maximum of 4.1% shortly after, at 260 s (4:20). These peak values occurred just prior to the start of suppression at 237 s (3:57). Afterward, the gas concentrations began returning to ambient conditions. Hydraulic ventilation increased the rate at which the gas concentrations returned to ambient conditions. At the start of hydraulic ventilation (312 s (5:12)), the gas concentrations were 17.8% O_2, 0.5% (5000 ppm) CO, 2.6% CO_2. Ambient conditions (20.95% O_2, 0.0% (0 ppm) CO, 0.0% CO_2) were met at 450 s (7:30), 138 s after the start of hydraulic ventilation.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

Figure 3.44: Living room gas concentrations for Experiment 1D. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

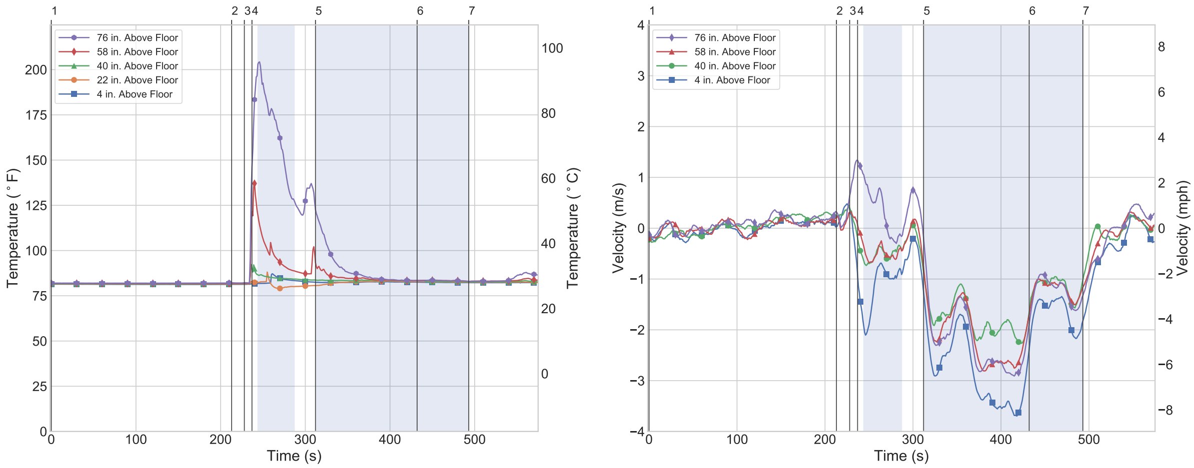
The pressure measurements in each room of the fire apartment were closely aligned (Figure 3.45). The pressure in each room peaked at 200 s (3:20), with values of 110 Pa—112 Pa in the bedroom (fire room), living room, and kitchen. Pressure inside the apartment dropped to approximately 20 Pa before the bedroom window was vented at 228 s (3:48). Note: The pressure tap in the kitchen was impacted by the hose stream at the start of suppression, and as a result, data from that sensor thereafter is omitted. The pressure in the living room and bedroom were approximately 0 Pa from the start of suppression until the start of hydraulic ventilation. During hydraulic ventilation, pressures in both the bedroom and living room became negative as hydraulic ventilation entrained air from these compartments. The pressures reached minimums of -17 Pa in the bedroom and -10 Pa in the living room. The pressure tap in the bedroom was damaged during the hydraulic ventilation at 432 s (7:12), so the remainder of the data is omitted from Figure 3.45. Following the ventilation of the kitchen window and living room sliding glass door, the pressure in the living room increased toward ambient as less air was entrained through the living room. The pressure in the living room returned to ambient conditions after hydraulic ventilation stopped.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

Figure 3.45: Fire apartment pressures for Experiment 1D. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened at 237 s post ignition to allow for the suppression crew to enter the apartment, but was then held mostly closed for door control. This initial act of opening the door allowed the combustion gases in the fire apartment to flow into the stairwell and gases in the hallway to flow into the apartment. Figure 3.46 shows the temperatures and velocities recorded at the fire apartment door. After the apartment door was opened, temperature at the top sensor increased to 200 °F as combustion gases flowed out of the apartment at approximately 1 m/s (2 mph). At the 58 in. elevation and below, flow was initially into the apartment at 0.5 m/s (1 mph) as the vent in the fire room acted as the predominant exhaust vent for the higher pressure fire room gases. The partially closed door limited the exchange of gas at the doorway compared to full-open door in Experiment 1C (see Figure 3.33). Following suppression, gas flow out the door slowed toward 0 m/s because the production of combustion gases had stopped. The thermocouple at the 58 in. elevation did measure an increase in temperature despite the inflow, due to heat transfer from the hot gases exhausting through the doorway above the probe.



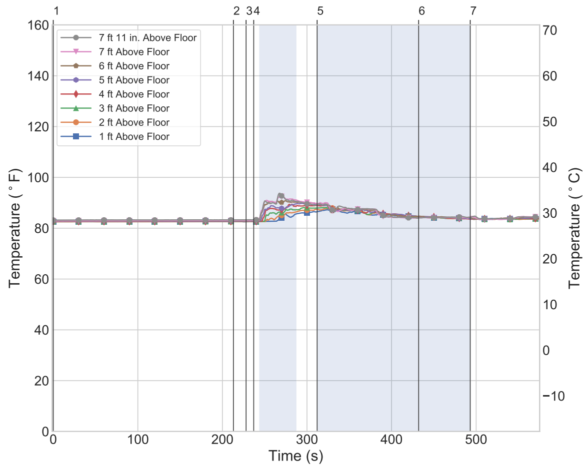
(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

Figure 3.46: Apartment A door temperatures and velocities for Experiment 1D. Blue shaded regions indicate time and duration of water flow.

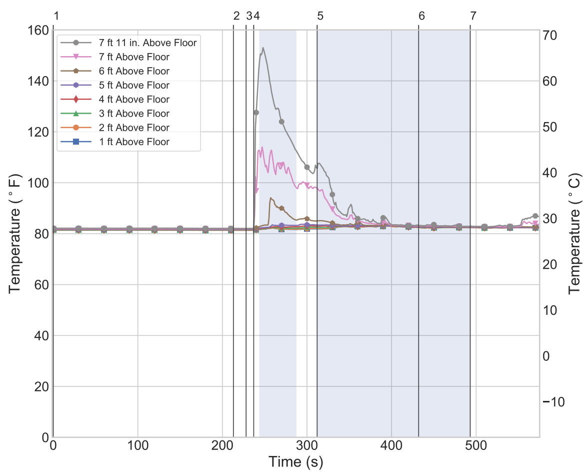
At 312 s, the apartment door was opened at the start of hydraulic ventilation. The flow at the doorway became a full-inlet (i.e., flow into the apartment) between -2 m/s (4 mph) and -3 m/s (6 mph). Temperatures at the 76 in. and 58 in. thermocouple locations both decreased back to ambient levels. At 432 s post-ignition (120 s after the start of hydraulic ventilation), the kitchen window and living room sliding glass door were opened. The additional apartment ventilation decreased the flow through the doorway to the stairwell to approximately 1 m/s (2 mph). The vents opened other supply pathways for the air being entrained and exhausted out the fire room window because of the flowing narrow fog stream, which caused less air to be entrained from the stairwell. After the line was shut down, gas flows at the fire apartment door returned to ambient levels.

The temperatures measured on each floor of the stairwell remained ambient and steady (about 85 °F) until the fire apartment door was opened (see Figure 3.47). After the apartment door was opened at 237 s (3:57), temperatures on the first and second floors increased as smoke from the previously closed fire apartment door began to fill the stairwell. On the second floor, the temperature 1 in. below the ceiling reached a peak of 95 °F at 267 s (4:27). Temperatures at all elevations on the second floor then steadily returned to ambient conditions, reaching below 85 °F by 427 s (7:07). On the first floor, temperatures measured 6 ft above the floor and higher showed a sharp

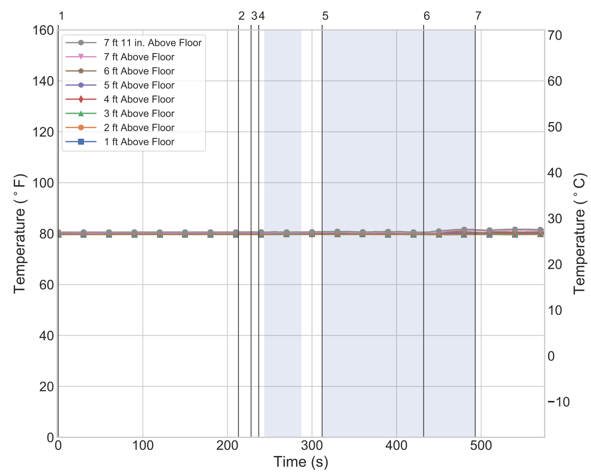


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493



(b) First-Floor Stairwell

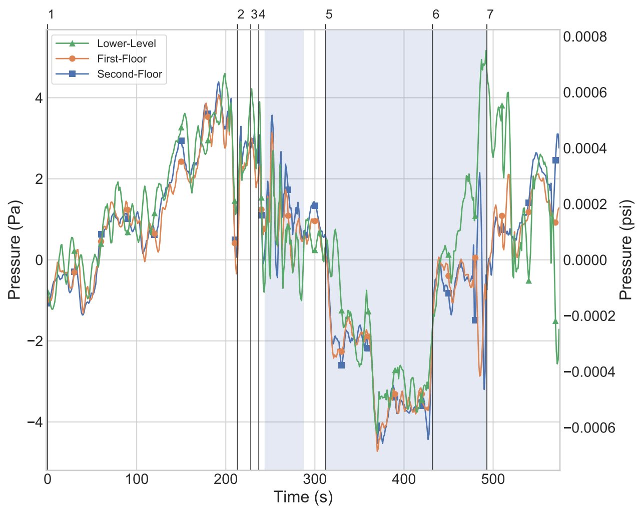


(c) Lower-Level Stairwell

Figure 3.47: Stairwell temperatures for Experiment 1D. Blue shaded regions indicate time and duration of water flow.

spike corresponding with the opening of the apartment door; the highest temperature was 155 °F measured 1 in. below the ceiling. The temperatures then decreased toward ambient conditions, reaching below 85 °F by 396 s (6:36). Temperatures measured below 6 ft on the first floor did not experience a change throughout the experiment. Likewise, temperatures on the lower level of the stairwell did not experience a change throughout the experiment.

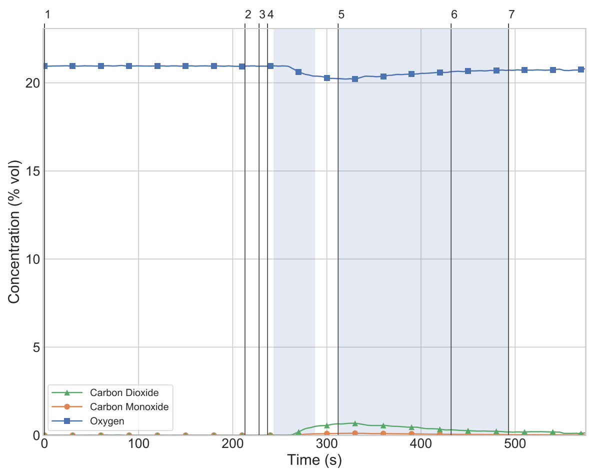
The time histories of the pressures in the stairwell are shown in Figure 3.48. The pressures in the stairwell increased gradually during the growth stage of the fire, reaching peaks of 4 Pa at 193 s (3:13) on each floor of the stairwell. At 213 s (3:33), pressure on each floor of the stairwell momentarily decreased as a result of the open door. The pressures in the stairwell then decreased toward 0 Pa during suppression. Between the start of hydraulic ventilation and venting the kitchen and living room, the stairwell pressures became negative as make-up air for the hydraulic vent was pulled from the exterior breezeway door, through the stairwell. The pressures reached minimums of -4 Pa. Opening vents in the kitchen and living room at 432 s (7:12) created new make-up air intake for the hydraulic vent, and thus less air flowed through the stairwell.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

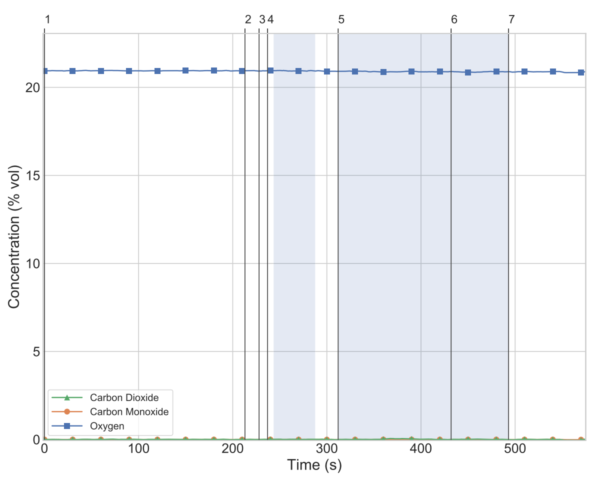
Figure 3.48: Stairwell pressures for Experiment 1D. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The gas concentrations on the lower level and first floor of the stairwell were not affected because coordinated door control and suppression limited the combustion gases that flowed from the apartment to the stairwell (see Figure 3.49). Similarly, there was only minimal response in the gas concentrations on the second floor. The minimum O_2 concentration on the second floor was 20.2%. The maximum CO and CO_2 concentrations were 0.1% (1000 ppm) and 0.7%, respectively.

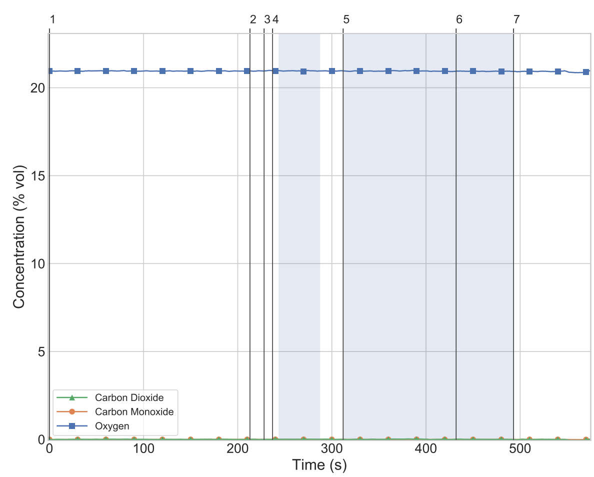


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493



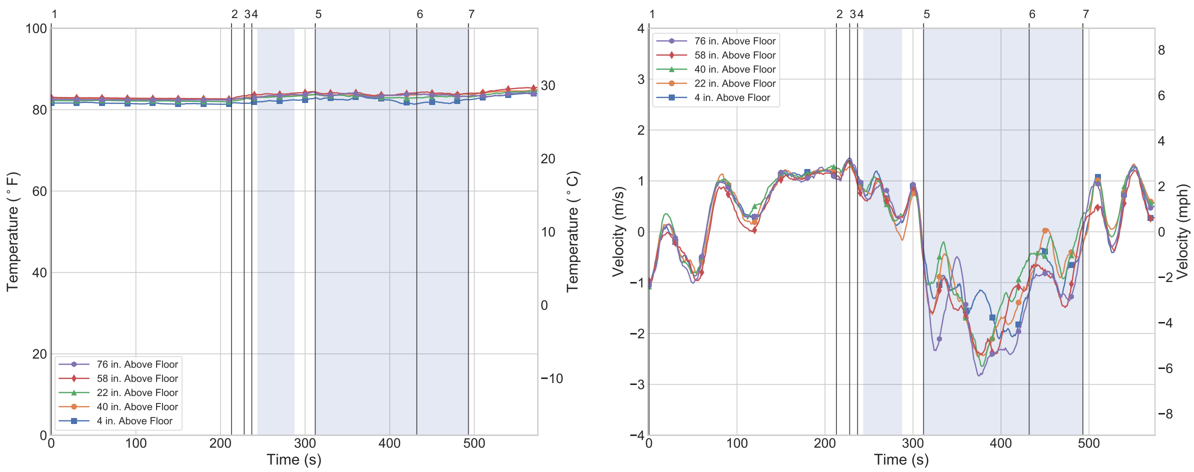
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.49: Stairwell gas concentrations for Experiment 1D. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The temperatures and velocities recorded at the exterior breezeway door are shown in Figure 3.50. Hydraulic ventilation began at 312 s (5:12), entraining gases from throughout the structure and exhausting them from the bedroom window. Make-up air for the hydraulic vent was pulled through the exterior door, creating unidirectional flow into the structure at speeds up to 3 m/s (7 mph). Opening vents in the kitchen and living room at 432 s (7:12) created new make-up air intake for the hydraulic vent, reducing the speed through the exterior door to less than 1.5 m/s (3 mph). Flow through the exterior door slowed to 0 m/s after hydraulic ventilation ended at 493 s (8:13). The temperature at the exterior door reflected ambient conditions (about 85 °F) throughout the experiment.



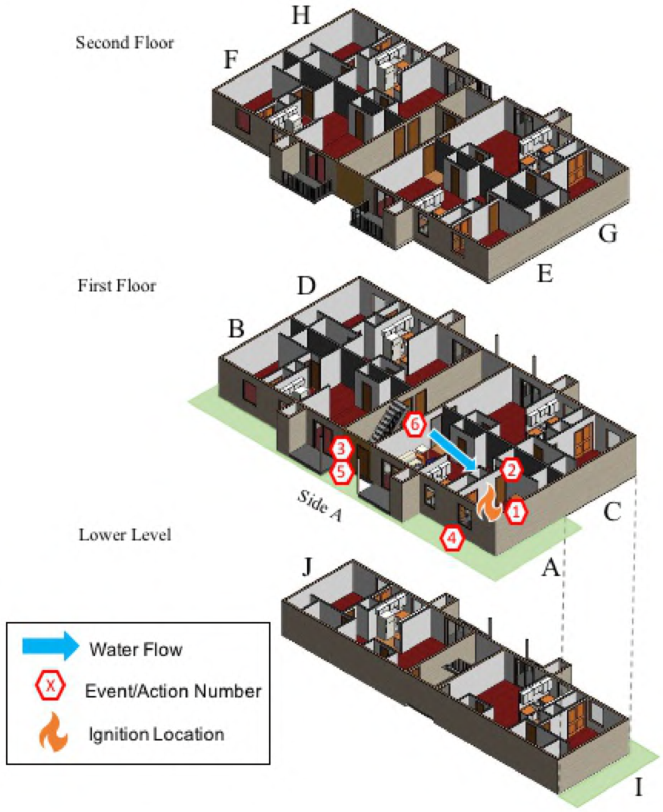
(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	213
3	Vent bedroom window	228
4	Open apartment door (door controlled); flow-and-move to fire room	237
5	Begin hydraulic ventilation	312
6	Ventilate kitchen and living room	432
7	End hydraulic ventilation	493

Figure 3.50: Exterior door temperatures and velocities for Experiment 1D. Blue shaded regions indicate time and duration of water flow.

3.5 Experiment 1E – Isolated First-Floor Apartment Fire with Positive Pressure Ventilation Simultaneous with Interior Suppression

Experiment 1E was conducted in Apartment A of 1978 Kimberly Village Lane, and was it designed to evaluate the use of PPV simultaneous with interior suppression. This is commonly referred to as a PPA. Horizontal ventilation followed later in the experiment. The fire originated in a first-floor apartment bedroom. Prior to ignition, all exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was open at the start of the experiment, but closed during the fire-growth stage due to pressure changes caused by the fire. There was minimal smoke and no fire showing on the exterior of the structure at the start of firefighter intervention. Firefighter intervention included venting the bedroom (fire room) window, followed by initiation of fan operations at the exterior door, and then entry to the fire apartment by the suppression crew for interior flow-and-move suppression into the fire compartment. Figure 3.51 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Bedroom door closed	03:35	215
3	Open exterior door	04:00	240
4	Vent bedroom window	04:18	258
5	Begin positive pressure attack	04:23	263
6	Open apartment door; flow-and-move to fire room	04:25	265

Figure 3.51: Time and sequence of actions and events for Experiment 1E.

The experimental volume included the fire apartment and the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.52 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

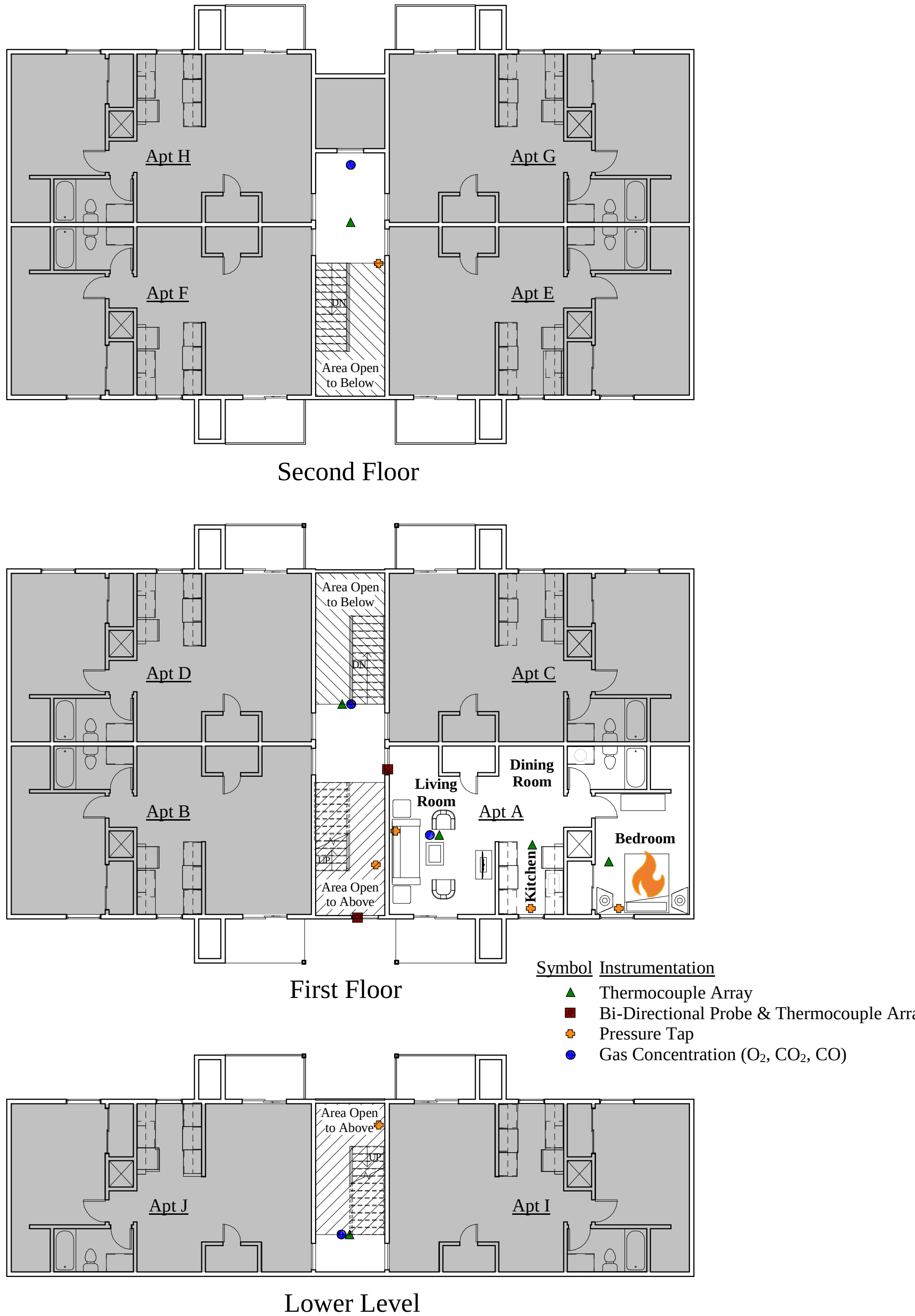


Figure 3.52: Instrumentation locations in Experiment 1E.

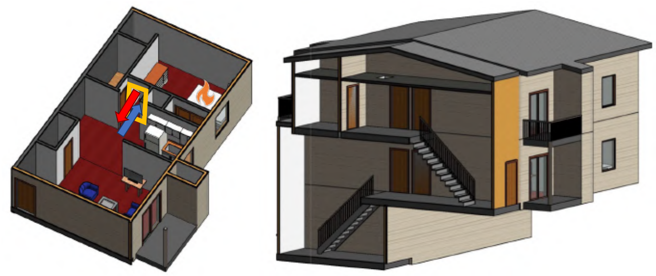
The bedroom, kitchen, and living room were furnished with the fuel loads described and photographed in Section 2.5.

The fire in Experiment 1E was ignited in a small, plastic waste container placed next to the head of the bed (t = 0 s). Fire growth was uninhibited in the fire apartment until the bedroom door closed. The bedroom door was intended to remain open according to the experimental design, but it closed due to pressure changes caused by the fire. The door closing was identified from an interior camera at 215 s (3:35) post ignition. About 30 s after the door closed (246 s (4:06)), the smoke layer in the bedroom descended to the floor. The fire became ventilation-limited as a result of the closed bedroom door, and was effectively extinguished prior to firefighter intervention. Before the bedroom door closed, a smoke layer had formed throughout the fire apartment. The smoke layer had descended approximately half the height of the apartment and did not appear to descend further after the bedroom door closed. There was no smoke visible in the stairwell prior to the suppression crew opening the fire apartment door.

Fire department intervention began 15 s after the bedroom door closed as the fire room temperatures began to decrease. The first fire department intervention was the opening of the exterior breezeway door at 240 s (4:00) post ignition. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. At approximately the same time the suppression crew made entry (258 s (4:18) to the breezeway), a separate crew broke the bedroom (fire room) window to provide horizontal ventilation. From an exterior view of the bedroom window, there was no visible fire in the bedroom after the window was broken, an indication the fire had decayed following the bedroom door closing.

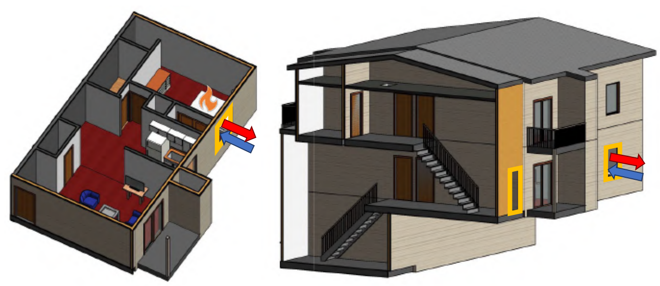
At 263 s (4:23), a fan was positioned at the exterior breezeway door to provide PPV for the attack. The fan utilized during this experiment was a 24 in. gasoline-powered positive pressure ventilator. It was positioned 6 ft back from the exterior breezeway door at full-tilt (approximately 20 deg.). The fan was rated to flow roughly 18,000 CFM. At 265 s (4:25), 7 s after the bedroom window was opened, the suppression crew opened the apartment door, flowed water at 160 gpm from a 7/8 in. smooth bore nozzle attached to 200 ft of 1 3/4 in. hoseline, and advanced to the bedroom (fire room) while continuing to flow. The hoseline was operated in an O pattern, open for a total of 49 s, and flowed 109 gallons of water in the initial interior suppression operation. Upon reaching the bedroom, the crew discovered the bedroom door was closed and the fire was already extinguished. Overhaul operations were conducted as needed.

The flow of combustion gases and fresh air during Experiment 1D are sketched in Figure 3.53. As the fire grew in the bedroom, high-temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the kitchen, dining room and living room in the apartment. Entrainment from the fire plume caused air to be drawn through the bedroom doorway into the fire compartment, which led to fire growth (see Figure 3.53a). Pressure build up in the fire room resulted in the bedroom door closing, isolating the fire from the rest of the apartment (see Figure 3.53b). The fire consumed the remaining oxygen available for combustion in the bedroom and began to decay. Firefighters vented the bedroom (fire room) window; however, the fire had already extinguished due to lack of oxygen. The open window allowed the bedroom to naturally ventilate (see Figure 3.53c). About 5 s later, firefighters began PPA and entered the structure for interior suppression. When firefighters opened the bedroom door, it created a flow path with an intake at the exterior breezeway door and an exhaust at the bedroom window. Fresh air, driven by the fan, replaced the combustion gases that exhausted from the bedroom window (see Figure 3.53d).

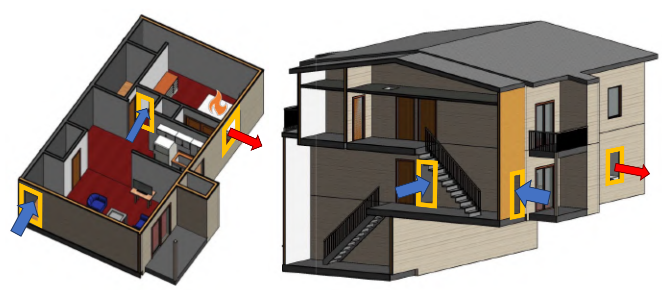


(a) Prior to the Bedroom Door Closing

(b) After the Bedroom Door Closed



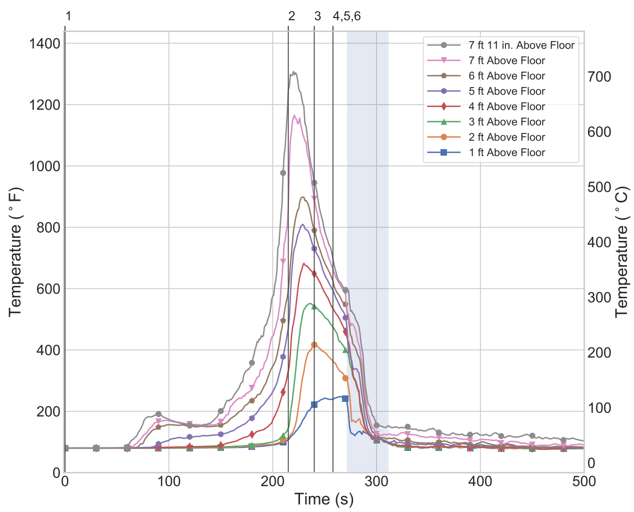
(c) After Venting the Bedroom Window



(d) After Starting PPA and Firefighter Entry to the Bedroom

Figure 3.53: Changes in flow during Experiment 1E. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

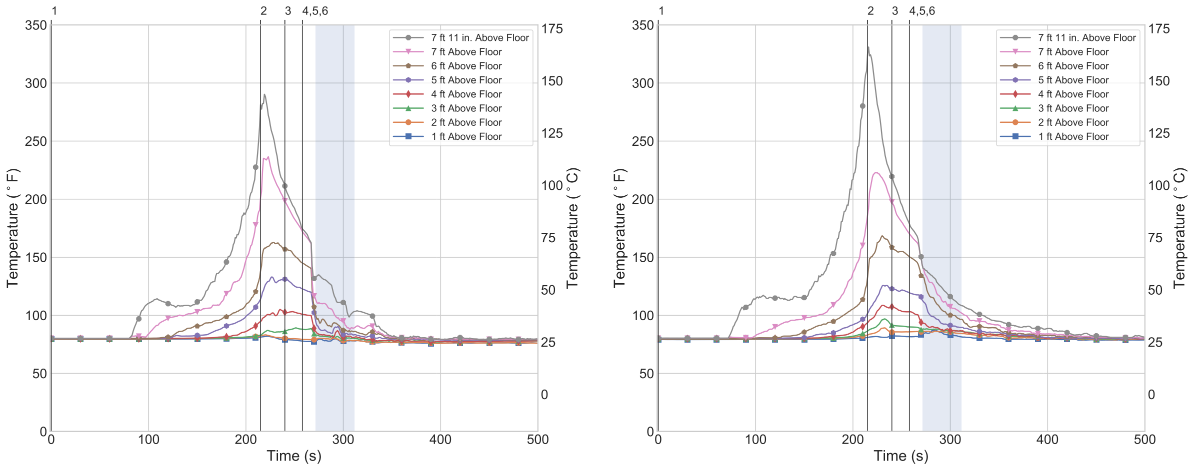
The time histories of the fire room temperatures are presented in Figure 3.54. Temperatures near the bedroom ceiling began to increase 60 s (1:00) post ignition and continued to rise steadily until the bedroom door closed at 215 s (3:35). The temperature began to decline 5 s later as the fire began to run out of oxygen. The peak temperatures occurred between 220 s (3:40) and 249 s (4:09), and ranged from 1300 °F 1 in. below the ceiling to 250 °F 1 ft above the floor. When the suppression crew entered the apartment at 265 s (4:25), the bedroom temperatures ranged from 600 °F 1 in. below the ceiling and 240 °F 1 ft above the floor. Despite the closed bedroom door separating the suppression crew from the bedroom, the start of suppression increased the rate at which the bedroom temperature decreased. When water application ended at 314 s (5:14), temperatures at all elevations in the bedroom were below 150 °F. The bedroom temperature continued to decrease toward ambient conditions for the remainder of the experiment.



	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

Figure 3.54: Fire room (bedroom) temperatures for Experiment 1E. Blue shaded regions indicate time and duration of water flow.

The temperatures in the kitchen and living room of the fire apartment showed a similar response to those measured in the bedroom, but with lower peaks (see Figure 3.55). The peak temperatures were 330 °F in the kitchen and 290 °F in the living room. Both peaks were measured 1 in. below the ceiling and occurred between 216 s (3:36) and 220 s (3:40), immediately after the bedroom door closed. The temperature in both rooms then decreased due to the fire becoming ventilation-limited and isolated to the bedroom. The start of suppression increased the rate at which the temperature in the kitchen and living room decreased. The temperature at all elevations in both rooms permanently fell below 100 °F by 336 s (5:36), 71 s after suppression started.



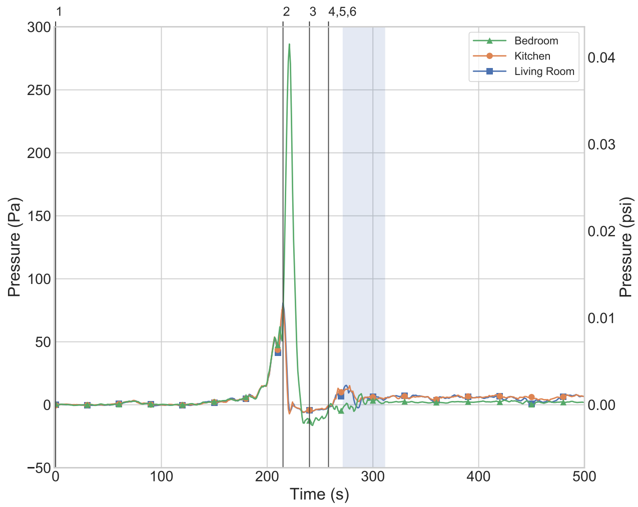
(a) Living Room (b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

Figure 3.55: Kitchen and living room temperatures for Experiment 1E. Blue shaded regions indicate time and duration of water flow.

The pressure measurements in each room of the fire apartment were closely aligned until the bedroom door closed (see Figure 3.56). The bedroom pressure notably deviated from the kitchen and living room pressures at 215 s (3:35), in the form of a steep increase as a result of the bedroom door closing. The bedroom pressure reached a peak of 287 Pa at 221 s (3:41), 6 s after the bedroom door closed, due to a combination of the air movement from the door closing and gas expansion of the elevated temperature combustion gases in the now isolated fire room compared to the full fire apartment. As the fire became ventilation-limited, the bedroom temperatures declined. The temperature drop led to gas contraction, which combined with a lack of air movement, dropped the bedroom pressure to -17 Pa at 243 s (4:03). The pressure began to increase toward 0 Pa before the window was opened at 258 s (4:18), and afterward it remained at ambient conditions as the bedroom pressure equalized with the outside.

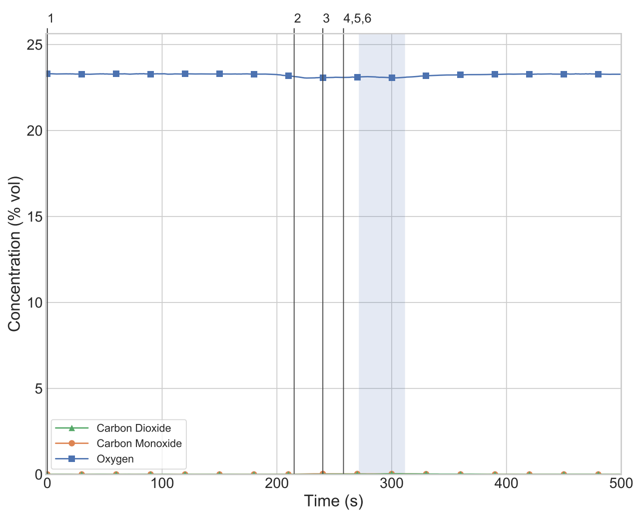
The pressures in the living room and kitchen both reached peaks of 80 Pa at 215 s (3:35) when the bedroom door closed. The pressures then decreased to minimums of -5 Pa to -7 Pa at 221 s (3:41) as the gases in those rooms cooled and contracted. The pressures remained negative until 260 s (4:20), when the suppression crew opened the apartment door and began flowing water. In response, the kitchen and living room pressures increased to 15 Pa. The pressures then decreased in response to suppression, but remained elevated at 5 Pa to 6 Pa for the remainder of the experiment due to airflow from the fan.



	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

Figure 3.56: Fire apartment pressures for Experiment 1E. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

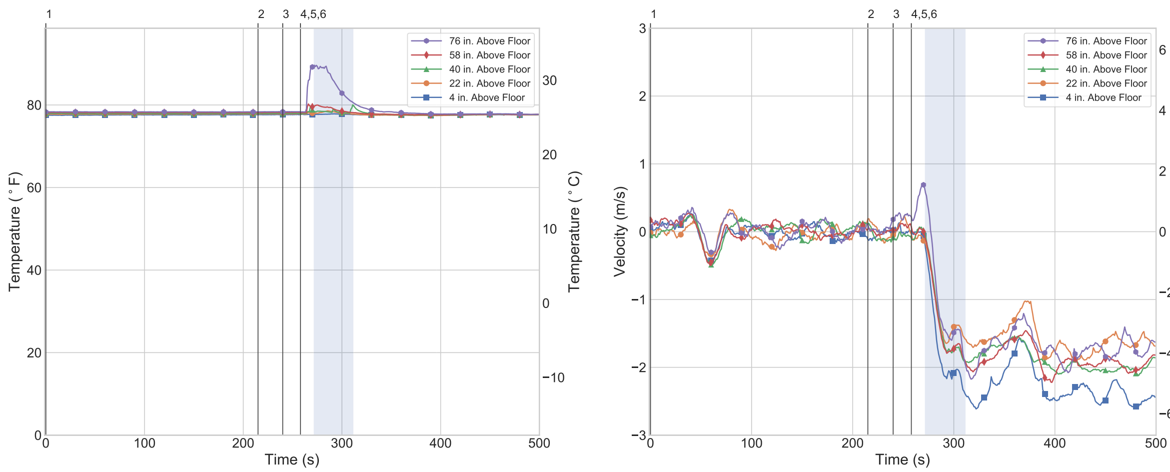
Gas concentrations in the living room of the fire apartment reflected ambient conditions throughout the experiment (see Figure 3.57). Video shows a smoke layer formed in the living room, but it did not descend to the elevation of the measurement location (4 ft above the floor).



	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

Figure 3.57: Living room gas concentrations for Experiment 1E. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened at 265 s (4:25) post ignition, which allowed the combustion gases in the fire apartment to flow into the stairwell. Figure 3.58 shows the temperatures and velocities recorded at the fire apartment door. After the suppression crew opened the apartment door, the temperature at the top sensor increased to 90 °F due to the combustion gases that flowed out of the apartment at approximately 1 m/s (2 mph). At the 58 in. elevation and below, the direction of flow was into the apartment due to the PPA. At 277 s (4:37), 12 s after the apartment door was opened, the structure became pressurized from the PPA, which resulted in unidirectional flow between 1 m/s (2 mph) and 3 m/s (7 mph) into the apartment. The temperature at the 76 in. elevation returned to below 80 °F by 315 s (5:15).

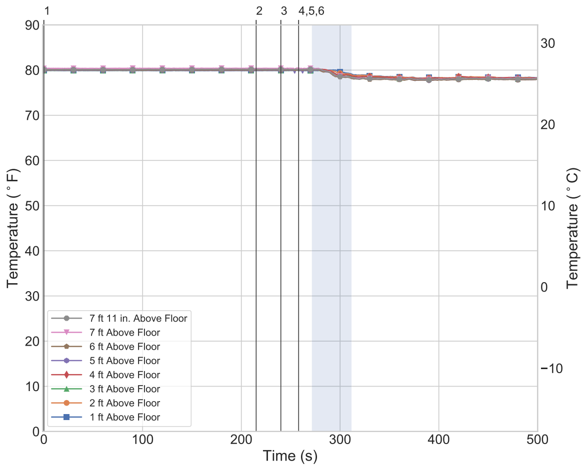


(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

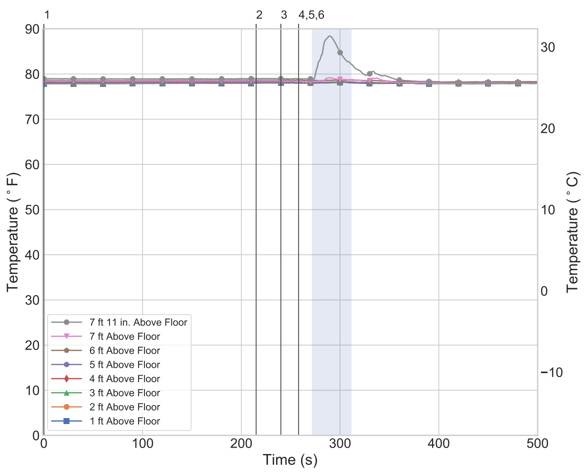
Figure 3.58: Temperatures and velocities at fire apartment (Apartment A) door for Experiment 1E. Blue shaded regions indicate time and duration of water flow.

The temperature on each floor of the stairwell remained near ambient conditions for the duration of the experiment (see Figure 3.59). The only exception was a small increase in temperature 1 in. below the first-floor ceiling starting at 274 s (4:34), 9 s after the door to the fire apartment was opened. Smoke released from the fire apartment into the stairwell increased the temperature at that location by 10 °F in 15 s. The temperatures then returned to ambient conditions.

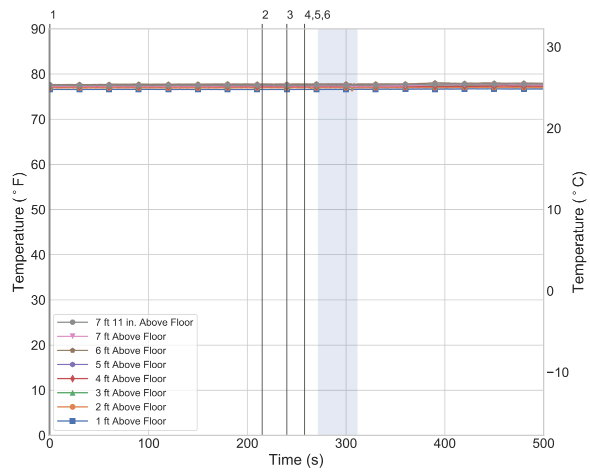


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265



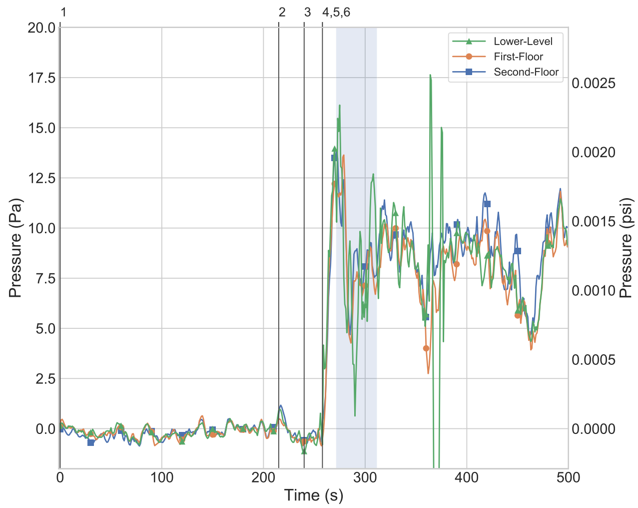
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

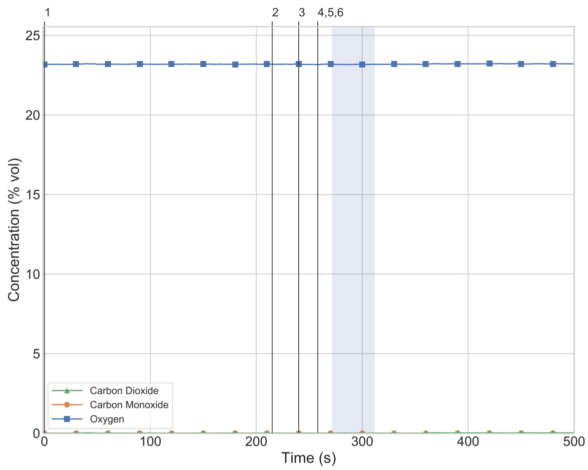
Figure 3.59: Stairwell temperatures for Experiment 1E. Blue shaded regions indicate time and duration of water flow.

Pressures in the stairwell remained near ambient conditions until the start of PPA at 263 s (4:23) (see Figure 3.60). The PPA elevated the stairwell pressures to between 4 Pa and 14 Pa for the remainder of the experiment. At about 365 s (6:05), the lower-level pressure tap was impacted by firefighter operations, resulting in a pressure spike. Gas concentrations measured on each floor of the stairwell were not affected because PPA limited the flow of combustion gases from the apartment to the stairwell (see Figure 3.61).



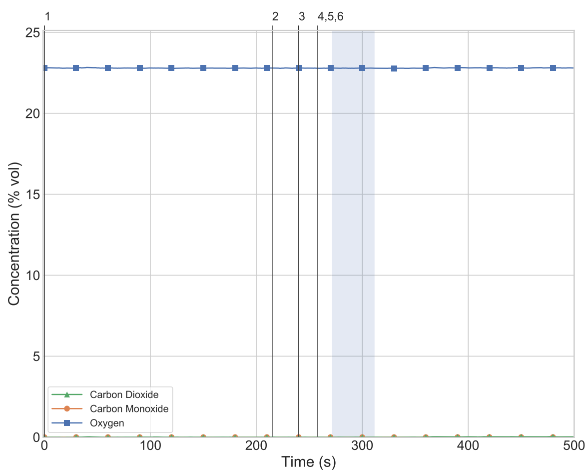
	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

Figure 3.60: Stairwell pressures for Experiment 1E. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

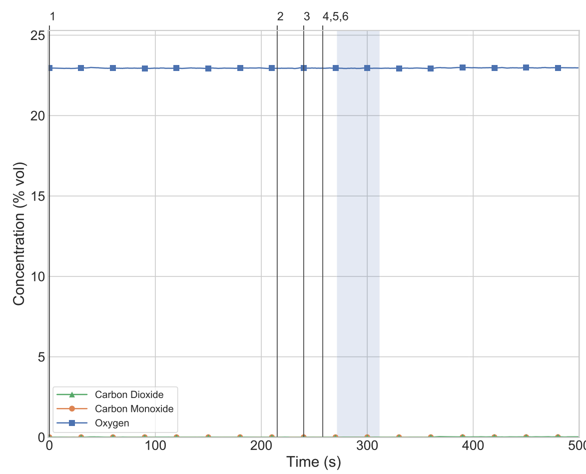


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265



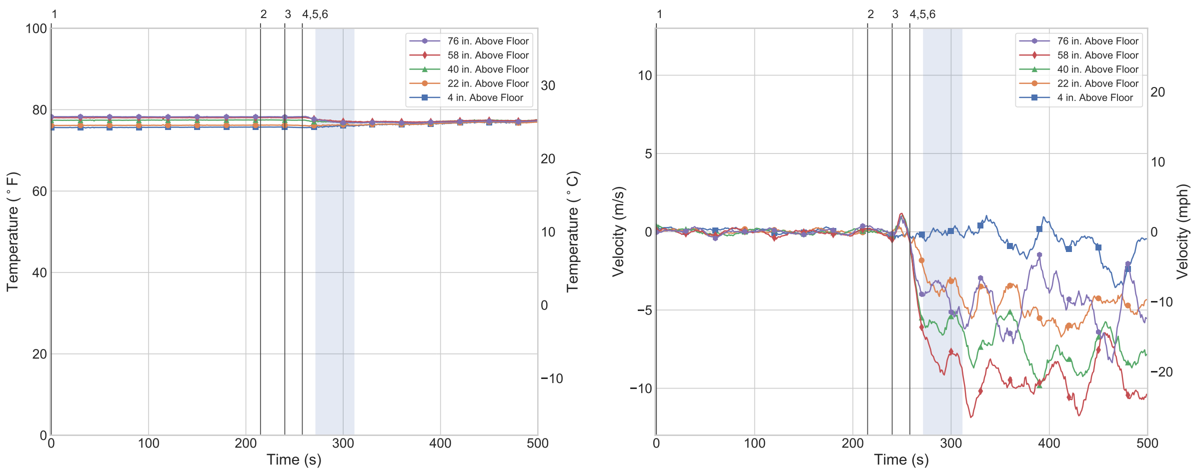
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.61: Stairwell gas concentrations for Experiment 1E. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The temperatures and velocities recorded at the exterior breezeway door are shown in Figure 3.62. The exterior door was opened at 240 s (4:00), allowing gases to flow out of the stairwell. Flow at the 40 in. elevation and above increased to 1 m/s (2 mph). PPA began shortly thereafter at 263 s (4:23), which lead to unidirectional flow into the structure. The flow was fastest near the center of the door, where the 40 in. and 58 in. elevations ranged from 5 m/s (11 mph) to 12 m/s (27 mph) into the structure. At the 22 in. and 76 in. elevations, there was 1 m/s (2 mph) to 8 m/s (18 mph) flow into the structure. The flow was slowest at the 4 in. elevation, which remained less than 4 m/s (9 mph). The temperature at the exterior door reflected ambient conditions (about 80 °F) throughout the experiment.



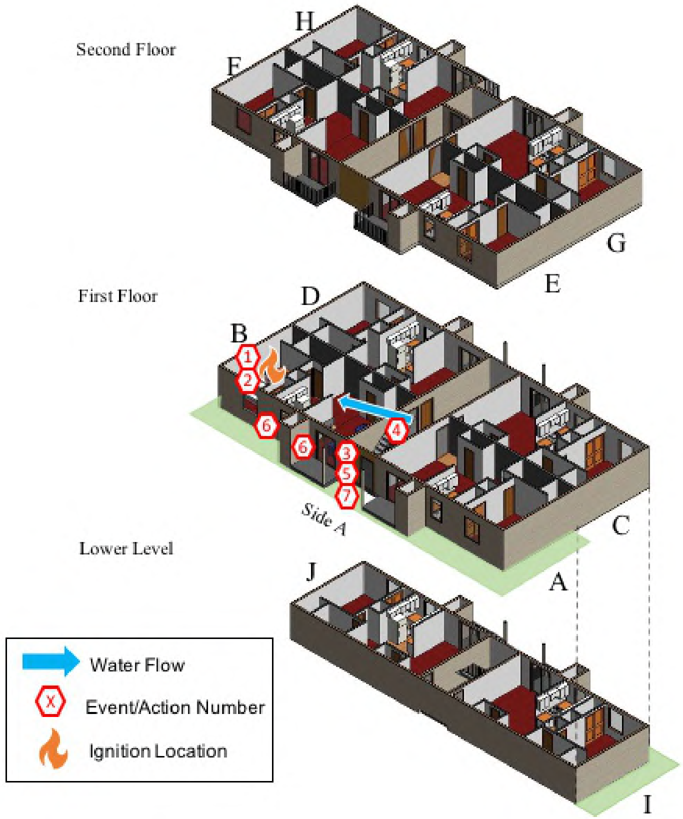
(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Bedroom door closed	215
3	Open exterior door	240
4	Vent bedroom window	258
5	Begin positive pressure attack	263
6	Open apartment door; flow-and-move to fire room	265

Figure 3.62: Exterior door temperatures and velocities for Experiment 1E. Blue shaded regions indicate time and duration of water flow.

3.6 Experiment 2A – First-Floor Apartment Fire with Positive Pressure Ventilation After Interior Suppression with Door Control

Experiment 2A was conducted in Apartment B of 1978 Kimberly Village Lane, and it was designed to evaluate the use of positive pressure ventilation (PPV) post interior suppression and door control at the entrance to the fire apartment. The fire originated in a first-floor apartment bedroom with the bedroom window open for the duration of the experiment. Prior to ignition, all other exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was open for the duration of the experiment. Fire was showing at the bedroom (fire room) window prior to firefighter intervention. Firefighter intervention included entry to the structure, followed by entry into the fire apartment with door control, and flow-and-move suppression into the fire compartment. After the initial suppression operation by the suppression crew, the fire apartment door was fully opened and a fan was positioned at the exterior door to the stairwell to provide PPV. Figure 3.63 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Flashover in bedroom	04:20	260
3	Open exterior door	05:00	300
4	Open apartment door (door controlled); flow-and-move to fire room	05:28	328
5	Begin positive pressure ventilation	07:15	435
6	Ventilate kitchen and living room	11:55	715
7	End positive pressure ventilation	13:58	838

Figure 3.63: Time and sequence of actions and events for Experiment 2A.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.64 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

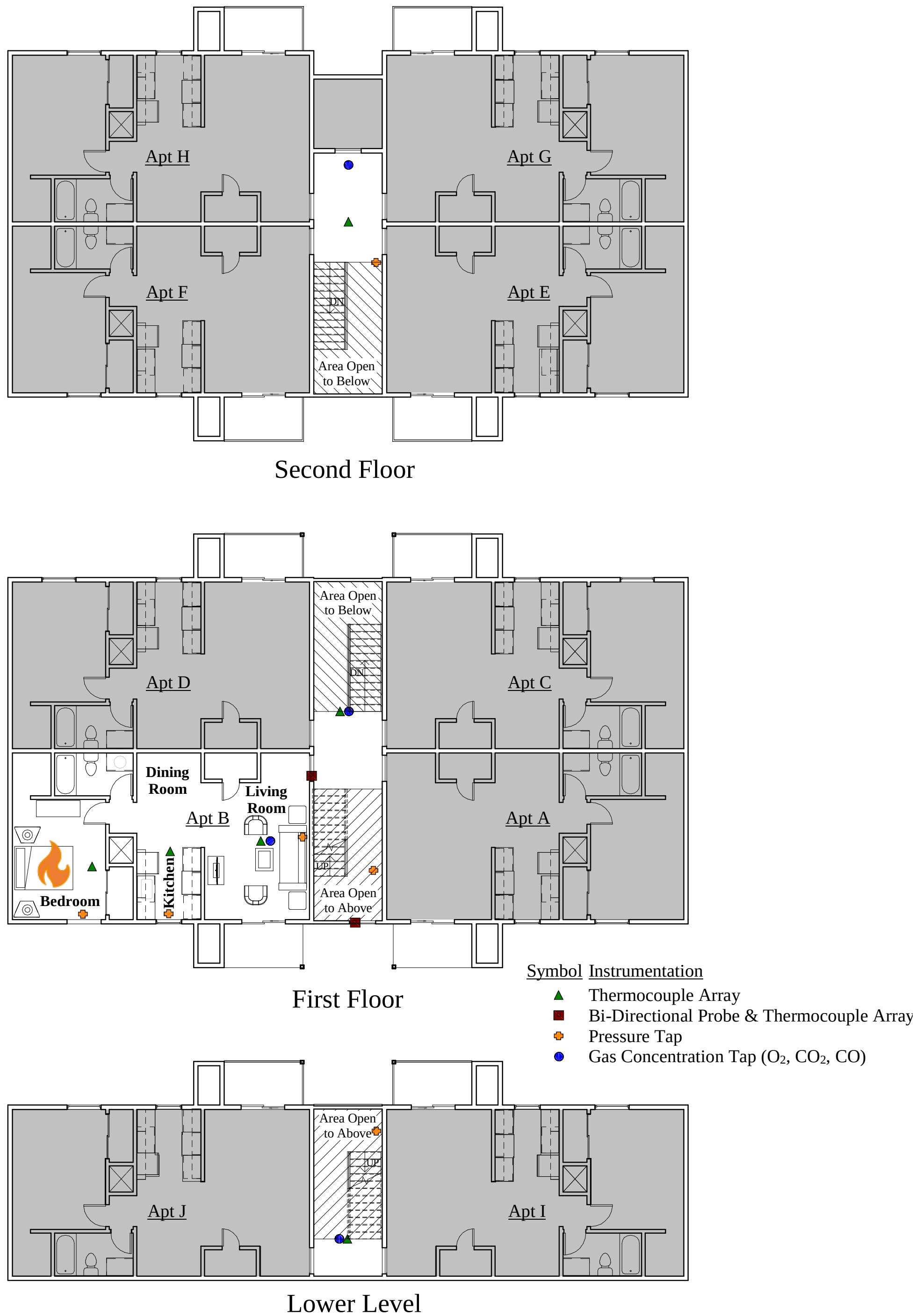


Figure 3.64: Instrumentation locations in Experiment 2A.

The bedroom, kitchen, and living room were furnished with the fuel loads described and photographed in Section 2.5. For this experiment, the bedroom fuel package was rotated 90 degrees within the space, such that the headboard was located on the left wall of the bedroom (fire room). The purpose of the change was to distance the fuel and ignition location from the open bedroom window, limiting the effects of the vent on initial fire growth.

The fire in Experiment 2A was ignited in a small, plastic waste container placed next to the head of the bed (t = 0 s). Flames began to extend out of the bedroom window at 199 s (3:19), and the room transitioned to flashover at 260 s (4:20). Figure 3.65a shows an image of the fire room from the exterior when it transitioned to flashover. The smoke layer continued to descend throughout the fire apartment and reached the kitchen and living room floors between 271 s (4:31) and 290 s (4:50). Zero visibility conditions in the fire apartment remained until fire department interventions occurred. There was no smoke visible in the stairwell prior to fire department intervention.

(a) Transition to Flashover in Bedroom (260 s)

(b) Opening Exterior Door (300 s)

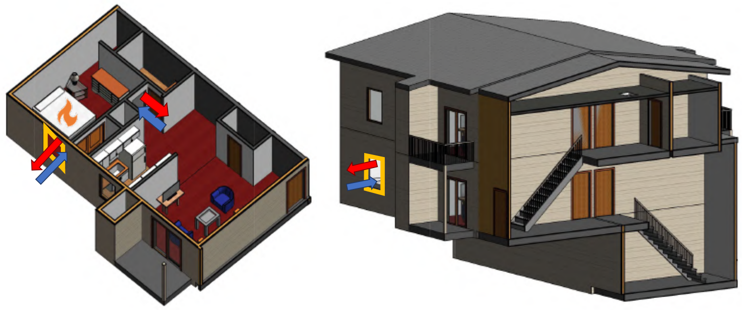
(c) 30 s after the Start of Suppression (358 s)

Figure 3.65: Images of the fire room (bedroom) window in Experiment 2A at flashover and during firefighter operations.

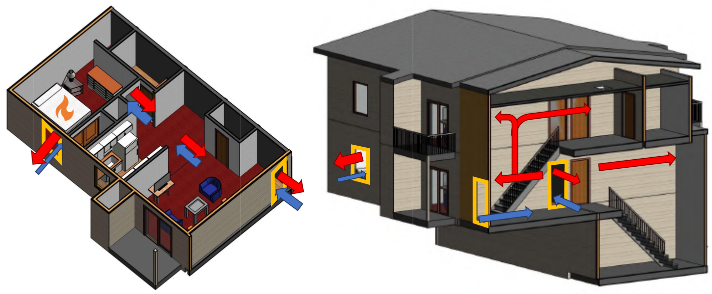
Fire department intervention began 40 s after the bedroom transitioned to flashover. The first fire department intervention was the opening of the exterior breezeway door at 300 s (5:00) post ignition. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. At 328 s (5:28), the suppression crew opened the apartment door and flowed water at 160 gpm from a 7/8 in. smooth bore nozzle operated in an O pattern, attached to 200 ft of 1 3/4 in. hoseline. The crew advanced to the bedroom (fire room) while continuing to flow. One firefighter remained at the apartment door to perform door control (i.e., the firefighter kept the door closed as far as allowed by the hoseline). The hoseline was open for a total of 66 s and flowed 152 gallons of water in the initial interior suppression operation, which successfully knocked down the fire. Water flow after 400 s (6:40) was utilized during overhaul operations. Figures 3.65b and 3.65c show images of the fire room from the exterior during firefighter operations.

At 435 s (7:15) post ignition, 41 s after completing the initial interior suppression operations, fan operations were initiated at the exterior breezeway door to provide PPV. The fan utilized during this experiment was a 24 in. gasoline-powered positive pressure ventilator. It was positioned 6 ft back from the exterior breezeway door at full-tilt (approximately 20 deg.). The fan was rated to flow roughly 18,000 CFM. The door-control firefighter opened the door at the same time. During PPV, the kitchen window and living room sliding glass door were opened at 715 s (11:55) to provide additional ventilation in the fire apartment. PPV continued until 838 s (13:58), for a total operation time of 403 s (6:43).

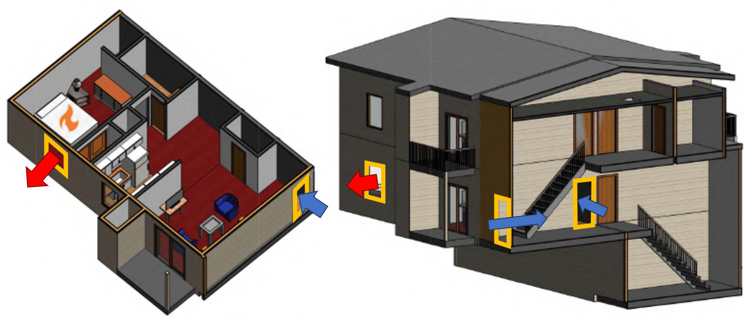
The flow of combustion gases and fresh air during Experiment 2A are sketched in Figure 3.66. As the fire grew in the bedroom, high-temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the common space in the apartment (the kitchen, dining room, and living room). Similarly, gases exhausted out of the top of the open bedroom window. Entrainment from the fire plume caused air to be drawn through the lower portions of the bedroom doorway and window into the fire compartment, which led to further fire growth (see Figure 3.66a). The open window provided sufficient exhaust of combustion gases and intake of fresh air to sustain combustion. Firefighters then entered through the exterior breezeway door and fire apartment door to begin interior suppression. The combustion gases flowed into the lower pressure enclosed stairwell through the top of the door as cooler, ambient air was entrained through the lower portion (see Figure 3.66b). Firefighters knocked down the fire, which stopped the production of gases. The start of PPV following suppression changed the flows through the fire compartment. Flow through the breezeway and apartment door transitioned to unidirectional inward. Flow through the bedroom window transitioned to unidirectional exhaust (see Figure 3.66c). The kitchen window and living room sliding glass door were opened later, providing additional exhaust vent area (see Figure 3.66d).



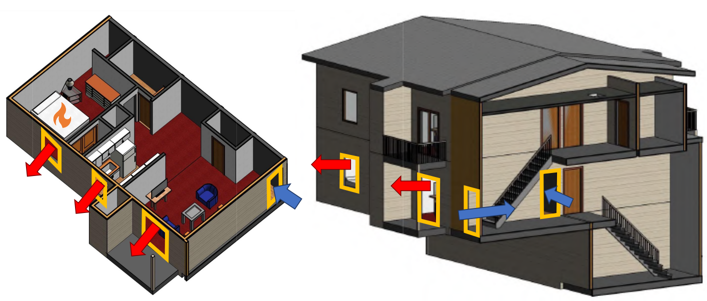
(a) Prior to Firefighter Entry



(b) After Firefighter Entry and Interior Suppression



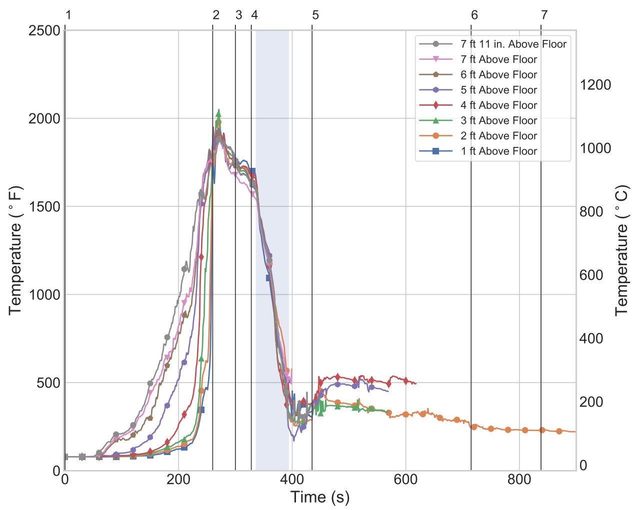
(c) After Starting PPV



(d) After Ventilating the Kitchen and Living Room

Figure 3.66: Changes in flow during Experiment 2A. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

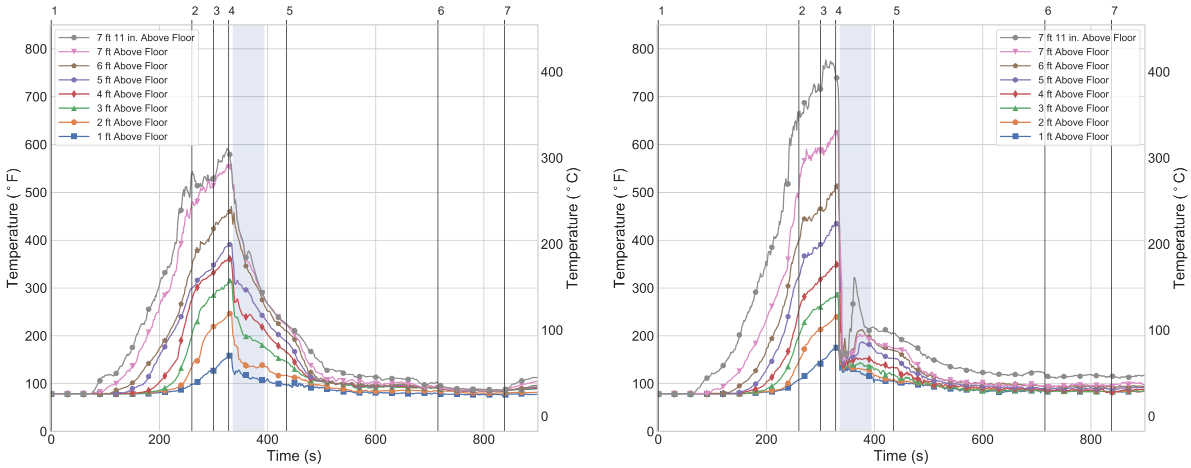
The time histories of the fire room temperatures are presented in Figure 3.67. The temperature near the bedroom ceiling began to increase 50 s post ignition as smoke began leaving the bedroom window. Temperatures at all elevations began to increase around 150 s (2:30), as fire spread across the head of the bed toward the open window. At 260 s (4:20), temperatures at all elevations exceeded 1100 °F, indicating flashover. The peak temperatures ranged between 1850 °F and 2050 °F at all elevations. Temperatures remained elevated until suppression began at 328 s (5:28), causing temperatures to decrease. The thermocouple array was damaged during suppression at 400 s (6:40), so several of the thermocouple measurements are omitted from Figure 3.67.



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

Figure 3.67: Fire room (bedroom) temperatures for Experiment 2A. Blue shaded regions indicate time and duration of water flow. Some thermocouple heights after 400 s (6:40) are omitted due to damage to the thermocouple array during suppression.

The temperatures in the kitchen and living room of the fire room increased steadily during the fire growth and post-flashover stages, then dropped in response to suppression (see Figure 3.68). Temperatures near the ceiling in both rooms began increasing around 75 s (1:15) after ignition. The peak temperatures in both rooms occurred immediately prior to suppression at 328 s (5:28). At their peak, temperatures in the kitchen ranged from 175 °F 1 ft above the floor to 775 °F 1 in. below the ceiling and temperatures in the living room ranged from 155 °F 1 ft above the floor to 590 °F 1 in. below the ceiling. Temperatures in the kitchen responded immediately to suppression and dropped below 200 °F at all elevations. Temperatures in the living room responded slightly slower, with temperatures at all elevations falling below 200 °F by 460 s (7:40), 132 s after suppression started.

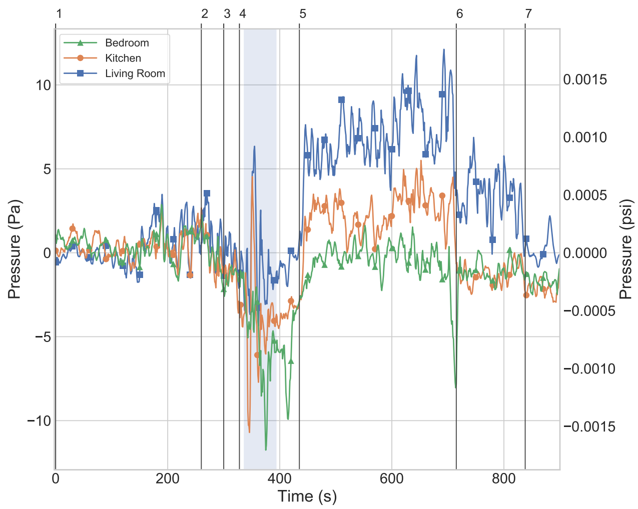


(a) Living Room (b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

Figure 3.68: Living room and kitchen temperatures for Experiment 2A. Blue shaded regions indicate time and duration of water flow.

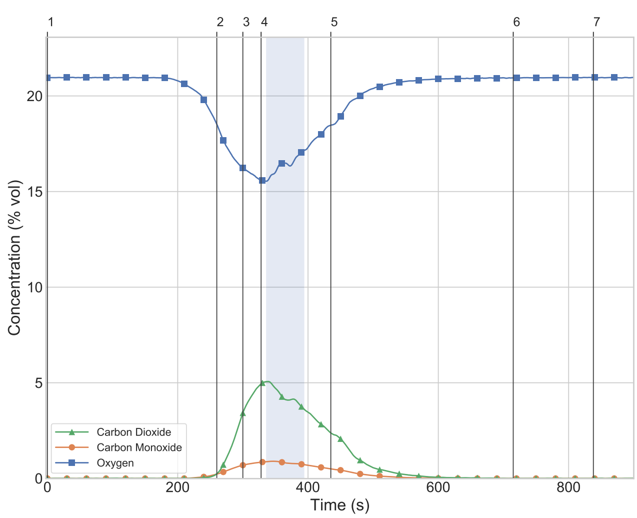
The time histories of the fire apartment pressures are presented in Figure 3.69. The open window in the bedroom (fire room) allowed combustion gases to flow from the fire room to the environment. This exhaust pathway limited the build-up of pressure in the fire apartment during the fire growth and fully developed stages. Therefore, pressures in each room of the fire apartment remained near 0 Pa until the start of suppression. Suppression caused the gases to cool and contract, creating negative pressure in the fire apartment. The pressures reached minimums of -12 Pa in the bedroom, -11 Pa in the kitchen, and -4 Pa in the living room. The pressures remained negative until the start of PPV at 435 s (7:15), which elevated the pressure in each room. The effect of PPV on pressures was greater at locations closest to the fan. The measurements nearest the open bedroom window were the least impacted because the open window allowed air exchange to equalize pressure in the compartment. Between the start of PPV and ventilating the kitchen and living room, the pressures were 4 Pa to 12 Pa in the living room, 0 Pa to 6 Pa in the kitchen, and ± 2 Pa in the bedroom. Ventilating the kitchen and living room at 715 s (11:55) allowed additional air exchange from the fire apartment to outside, further reducing the pressures in each room toward ambient conditions. After PPV ended at 838 s (13:58), the pressure in each room remained near 0 Pa.



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

Figure 3.69: Fire apartment pressures for Experiment 2A. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

Gas concentrations were measured in the living room of the fire apartment (see Figure 3.70). Gas concentrations began to change in response to the fire growth at around 220 s (3:40). The O_2 concentration decreased to a minimum of 15.5% at 335 s (5:35). At the same time, the CO and CO_2 concentrations reached maximums of 0.9% (9000 ppm) and 5.1%, respectively. These peak values coincided with the start of suppression at 328 s (5:28). Afterward, the gas concentrations began steadily returning to ambient conditions, which were achieved at approximately 600 s (10:00).

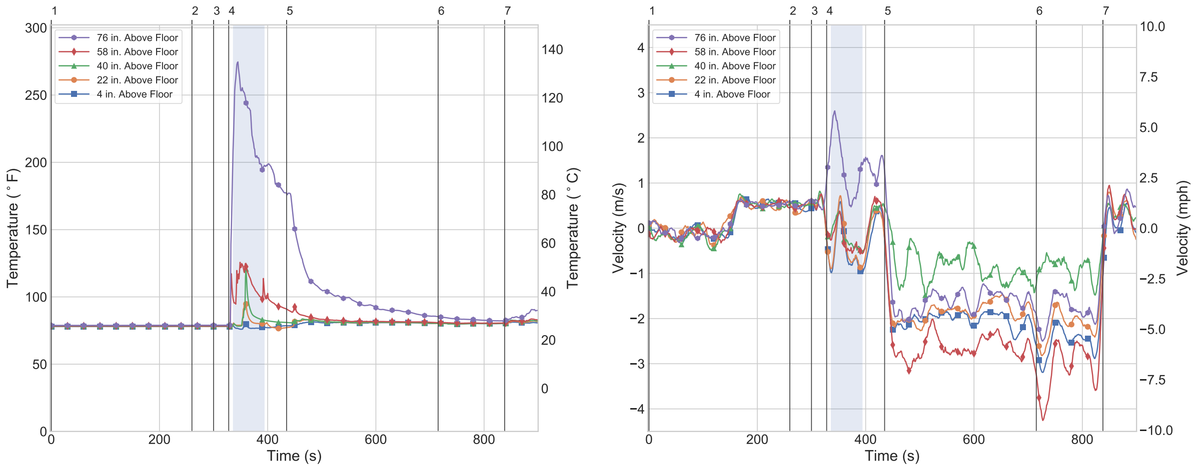


	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

Figure 3.70: Living room gas concentrations for Experiment 2A. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

Prior to the apartment door being opened, the velocities at the apartment door increased to 1 m/s (2 mph) as the pressure within the fire apartment increased, pushing air from around the apartment door into the stairwell. The apartment door was opened at 237 s (3:57) post ignition to allow for the suppression crew to the enter the apartment, but was then partially closed for door control. Figure 3.71 shows the temperatures and velocities recorded at the fire apartment door. After the apartment door was opened, temperature at the top sensor increased to 275 °F as gases flowed out of the apartment at approximately 2 m/s (4.5 mph). The 58 in. thermocouple showed an increase in temperature due to heat transfer from the combustion gas flowing out of the apartment. At the 58 in. elevation and below, flow was initially into the apartment at 0.5 m/s (1 mph) to 1 m/s (2 mph). The lower portion of the door acted as an intake and the vent in the fire room acted as the predominant exhaust vent for the higher pressure fire room gases. At 354 s post ignition, the apartment door was opened wider to allow for additional hose advancement. This is shown in the door velocities temporarily increasing to 0.5 m/s (1 mph) and a temperature rise measured on the 40 in. through 4 in. thermocouples. Following suppression, gas flow through the door slowed toward 0 m/s because the production of combustion gases had stopped.

PPV began at 435 s (7:15), causing unidirectional flow into the apartment at 0.5 m/s (1 mph) to 4 m/s (9 mph). The temperature at the top sensor dropped, falling below 100 °F by 550 s (9:10). After PPV ended at 838 s (13:58), the gas velocities returned to 0 m/s.

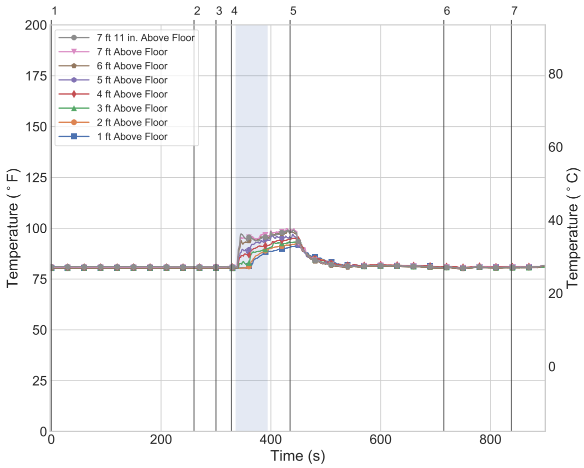


(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

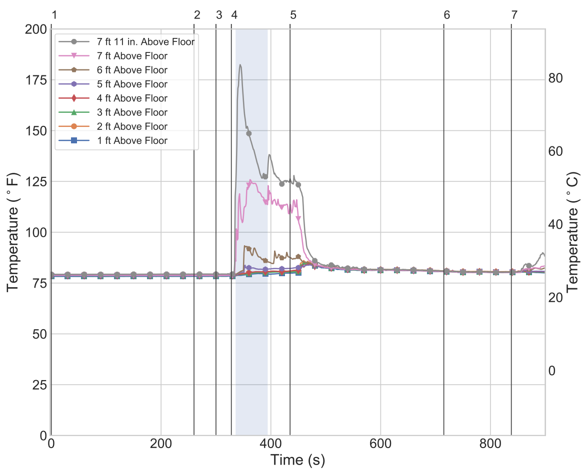
Figure 3.71: Temperatures and velocities at fire apartment (Apartment B) door for Experiment 2A. Blue shaded regions indicate time and duration of water flow.

The temperatures measured on each floor of the stairwell remained steady at approximately ambient temperature (about 80 °F) until the fire apartment door was opened at 328 s (5:28, see Figure 3.72). Temperatures on the first and second floors increased as smoke from the previously closed fire apartment door began to fill the stairwell. On the second floor, the temperature continued increasing until the start of PPV at 435 s (7:15), reaching peaks ranging from 90 °F 1 ft above the floor to 100 °F 1 in. below the ceiling. PPV quickly returned the second-floor temperature to ambient conditions. On the first floor, temperatures measured at 6 ft above the floor and higher showed a spike corresponding with opening the apartment door—the highest temperature was 185 °F measured 1 in. below the ceiling. As shown by the door velocity, the outflow from the apartment was impacted by the manipulation of the door. As a result, following the initial rise associated with entry to the apartment, temperatures began to decrease toward ambient conditions. This decrease was accelerated by the start of PPV. Temperatures measured below 6 ft on the first floor showed minimal change throughout the experiment. After PPV ended at 838 s (13:58), temperatures near the ceiling on the first floor recovered as the remaining smoke in the structure began to recirculate, but they did not exceed 90 °F. Temperatures measured on the lower level of the stairwell did not increase throughout the experiment.

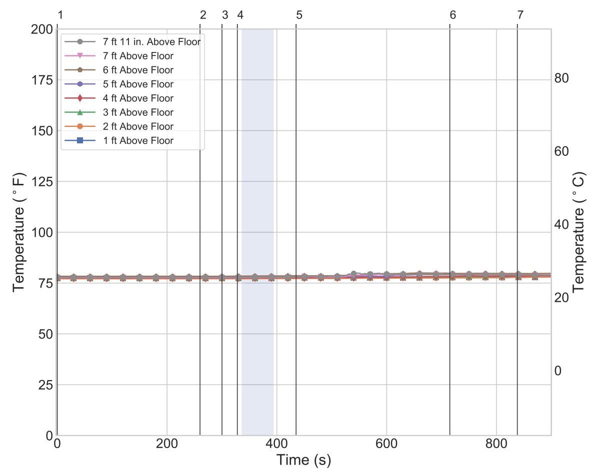


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838



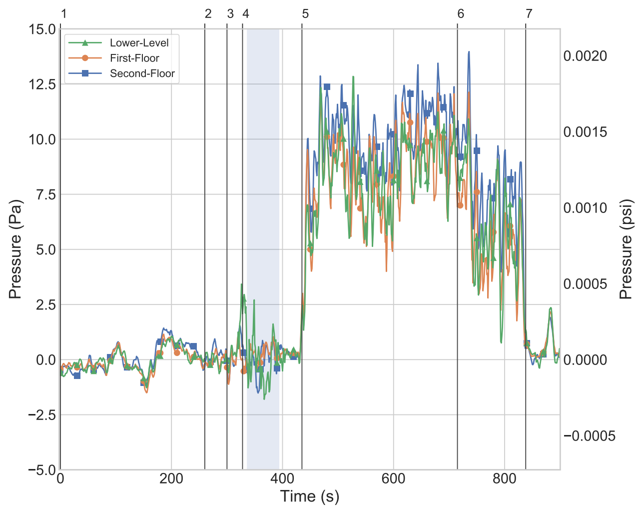
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.72: Stairwell temperatures for Experiment 2A. Blue shaded regions indicate time and duration of water flow.

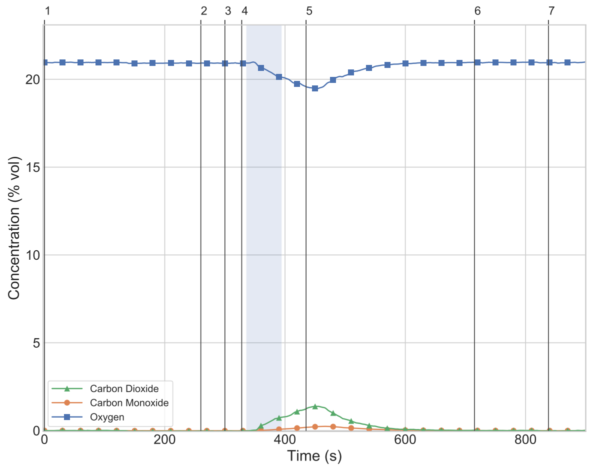
The pressures in the stairwell (see Figure 3.73) remained near ambient conditions until the start of PPV at 435 s (7:15). PPV elevated the pressures on each floor of the stairwell to approximately 8 Pa–9 Pa. The stairwell pressures remained in that range until the kitchen and living room were ventilated at 715 s (11:55), which relieved pressure in the stairwell, reducing it to approximately 6 Pa. When PPV ended at 838 s (13:58), the stairwell pressures returned to ambient conditions.



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

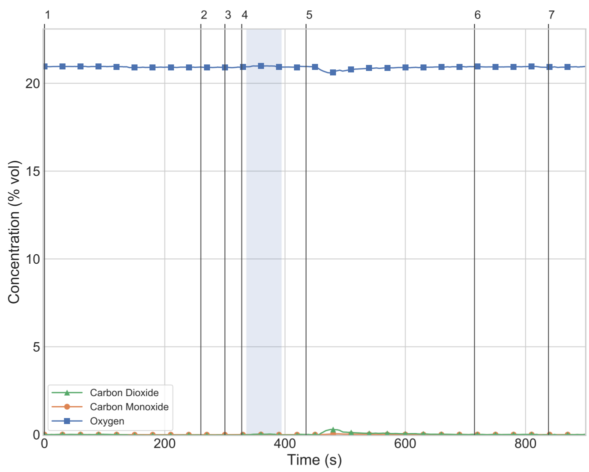
Figure 3.73: Stairwell pressures for Experiment 2A. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The gas concentrations in the stairwell remained near ambient conditions until the fire apartment door was opened at 328 s (5:28, see Figure 3.74). Smoke exhausted from the fire apartment door and rose to the top of the stairwell through buoyancy. The second-floor gas concentrations peaked at 451 s (7:31) with values of 19.4% O_2, 0.3% (3000 ppm) CO, and 1.4% CO_2. These peak values occurred 16 s after PPV began, which circulated fresh air into the stairwell and improved the second-floor gas concentrations. The first-floor and lower-level gas concentrations reflected ambient conditions throughout the experiment because the smoke layer did not descend to the elevation of the measurement locations. The only exception was the first-floor gas concentrations, which showed a small response after PPV began due to the mixing of smoke in the stairwell. The first-floor gas concentrations reached 20.5% O_2, 0.1% (1000 ppm) CO, and 0.3% CO_2 before returning to ambient conditions.

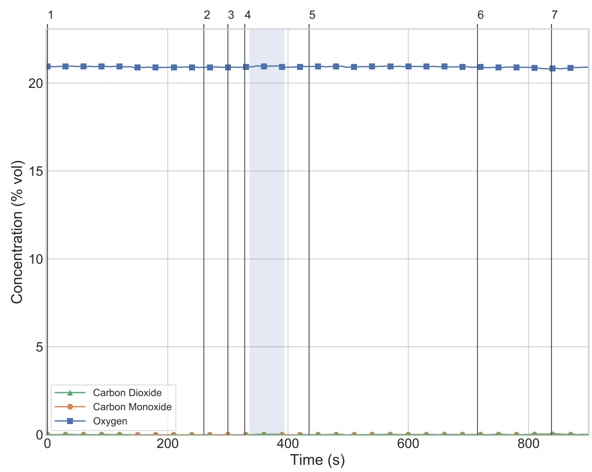


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838



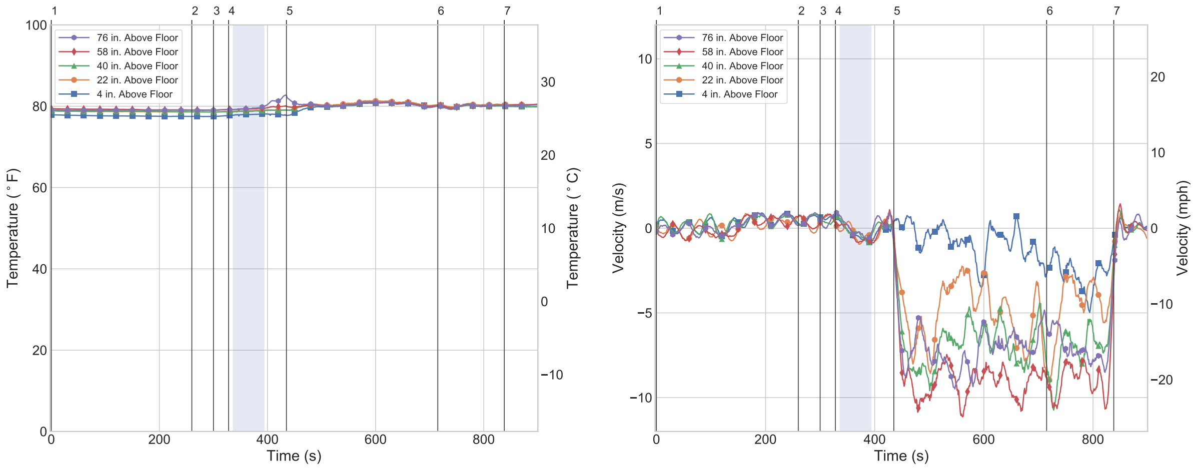
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.74: Stairwell gas concentrations for Experiment 2A. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The temperatures and velocities recorded at the exterior breezeway door are shown in Figure 3.75. PPV began at 435 s (7:15), which generated unidirectional flow into the structure. The flow was fastest near the center of the door, where the velocity at the 58 in. elevation ranged from 7 m/s (16 mph) to 11 m/s (25 mph) into the structure. At the 22 in., 40 in., and 76 in. elevations, there was 2 m/s (4 mph) to 10 m/s (22 mph) flow into the structure. The flow was slowest at the 4 in. elevation, which did not exceed 5 m/s (11 mph). The velocities through the exterior door remained steady throughout PPV, and returned to 0 m/s at all elevations after PPV ended. The temperature at the exterior door reflected ambient conditions (about 80 °F) throughout the experiment.



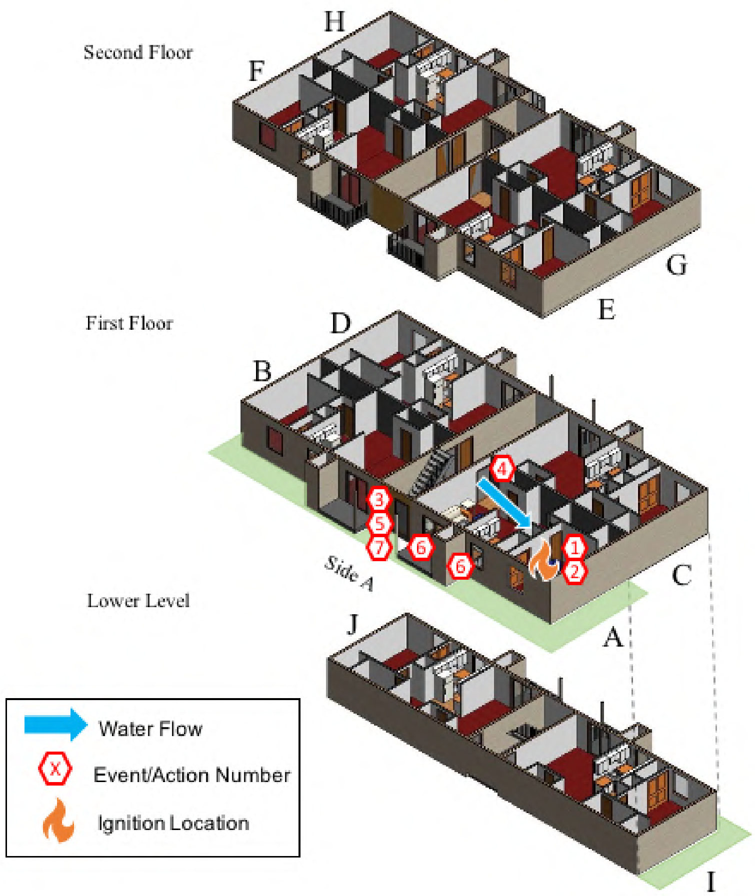
(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	260
3	Open exterior door	300
4	Open apartment door (door controlled); flow-and-move to fire room	328
5	Begin positive pressure ventilation	435
6	Ventilate kitchen and living room	715
7	End positive pressure ventilation	838

Figure 3.75: Exterior door temperatures and velocities for Experiment 2A. Blue shaded regions indicate time and duration of water flow.

3.7 Experiment 2B – First-Floor Apartment Fire with Positive Pressure Ventilation Simultaneous with Interior Suppression

Experiment 2B was conducted in Apartment A of 1978 Kimberly Village Lane, and it was designed to evaluate the use of positive pressure ventilation coordinated with simultaneous interior suppression for a fire that originated in a first-floor apartment bedroom. The experiment was an adaptation of Experiment 1E, in which the bedroom door closed during the fire's growth. Experiment 2B used the same apartment as in Experiment 1E due to the limited damage resulting from that experiment. Prior to ignition, the bedroom window was removed, and all other exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The door from the bedroom to the remainder of the common space in the fire apartment was removed prior to the experiment to avoid the risk of it closing as it did during Experiment 1E. Fire was showing at the bedroom (fire room) window prior to firefighter intervention. Firefighter intervention included entry to the structure and initiation of fan operations at the exterior door, followed by entry into the fire apartment and flow-and-move suppression into the fire compartment. Figure 3.76 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Flashover in bedroom	06:05	365
3	Open exterior door	06:12	372
4	Open apartment door; flow-and-move to fire room	06:35	395
5	Begin positive pressure attack	06:37	397
6	Ventilate kitchen and living room	13:27	807
7	End positive pressure attack	16:44	1004

Figure 3.76: Time and sequence of actions and events for Experiment 2B.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.77 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

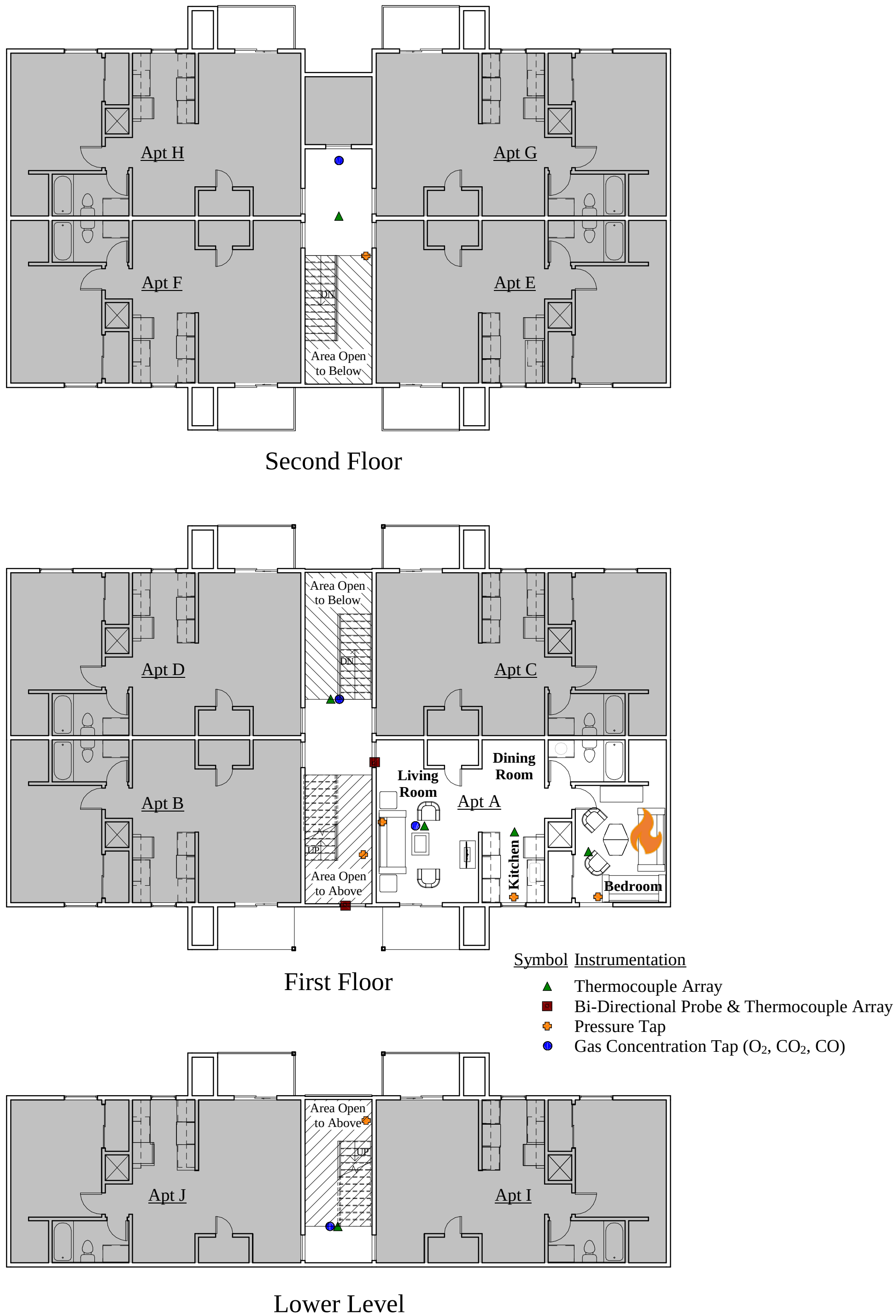


Figure 3.77: Instrumentation locations in Experiment 2B.

The fire apartment in Experiment 2B was the same as the one used in Experiment 1E. Figure 3.78 shows pre-test photographs of the interior of the bedroom. The bedroom ceiling and side A wall were patched with drywall in places where the original drywall had failed. It is important to note that unlike the other bedroom fires in this series, which used the fuel load as described in

Section 2.5, this experiment used a modified fuel load. To conduct a second experiment in the same unit as Experiment 1E within the confines of the overall series, the bedroom was furnished with fresh carpet and a combination of previously unused bedroom and living room fuels. This fuel load included two sofas, two barrel chairs, a dresser, and two night stands. The kitchen and living room were mostly undamaged from Experiment 1E, except for some minor soot staining. Therefore, the same fuels from Experiment 1E were used in those rooms.

(a) Looking Toward B/C Corner

(b) Looking Toward Side C

(c) Looking Toward A/D Corner

(d) Looking Toward Side A

Figure 3.78: Photographs of the interior of the bedroom in Experiment 2B.

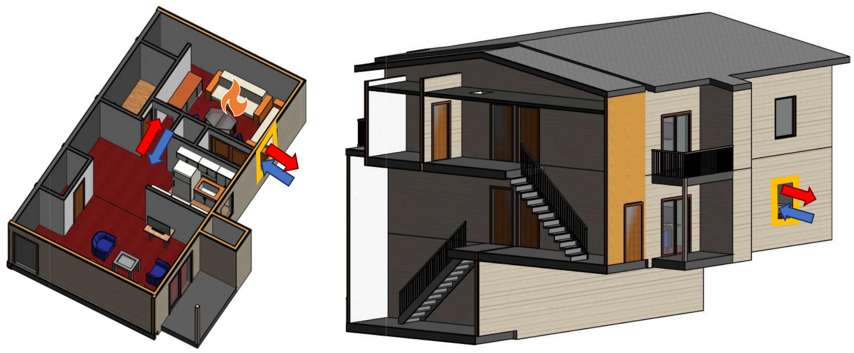
The fire in Experiment 2B was ignited with an electric match in the arm of the sofa furthest from the bedroom window (t = 0 s). Smoke began flowing out of the open bedroom window within 90 s (1:30) of ignition. Almost 5 min. later, at 313 s (5:13), flames began extending out of the bedroom window. A smoke layer formed throughout the fire apartment and descended to the floor at around 360 s (6:00). Shortly after, the bedroom (fire room) transitioned to flashover at 365 s (6:05). There was no smoke visible in the stairwell prior to fire department intervention.

The first fire department intervention was the opening of the exterior breezeway door at 372 s (6:12) post ignition, 7 s after the bedroom transitioned to flashover. Figure 3.79 shows an image of conditions on the side A exterior when the door was opened. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. At 395 s (6:35), the suppression crew opened the apartment door and began flowing water at 150 gpm from a combination nozzle attached to 200 ft of 1 3/4 in. hoseline. The suppression crew advanced to the bedroom (fire room) while continuing to flow. The hoseline was operated in an O pattern, was open for a total of 50 s, and flowed 105 gallons of water during the initial interior suppression operation, which successfully knocked down the fire. Any water flow after 450 s (7:30) was utilized during overhaul operations.

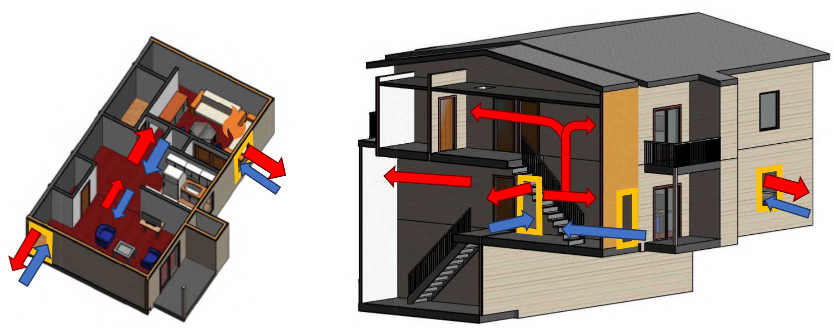
Figure 3.79: Image of the fire room (bedroom) window when the exterior breezeway door was opened in Experiment 2B.

At approximately the same time the suppression crew entered the fire apartment (397 s (6:37)), a fan was activated at the exterior breezeway door to provide PPA. The fan utilized during this experiment was a 24 in. gasoline powered positive pressure ventilator. It was positioned 6 ft back from the exterior breezeway door at full-tilt (approximately 20 deg.). The fan was rated to flow roughly 18,000 CFM. During PPA, the kitchen window and living room sliding glass door were opened at 807 s (13:27) to provide additional ventilation in the fire apartment. PPA continued until 1004 s (16:44), for a total operation time of 607 s (10:07).

The flow of combustion gases and fresh air during Experiment 2B are sketched in Figures 3.80 and 3.81. As the fire grew in the bedroom, high-temperature, lower density fire gases rose and began to fill the room from the top down. Once the hot gas layer reached the top of the door frame in the bedroom, gases spilled into the common space in the apartment (the kitchen, dining room, and living room). Similarly, gases exhausted out of the top of the open bedroom window. Entrainment from the fire plume caused air to be drawn through the lower portions of the bedroom doorway and window into the fire compartment, which led to further fire growth (see Figure 3.80a). The open window provided sufficient exhaust of combustion gases and intake of fresh air to sustain combustion. Firefighters then entered through the exterior breezeway and fire apartment doors and began interior suppression concurrent with PPV. Immediately after opening the door, there was a brief exhaust of combustion gases into the stairwell due to the higher pressure in the apartment (see Figure 3.80b).



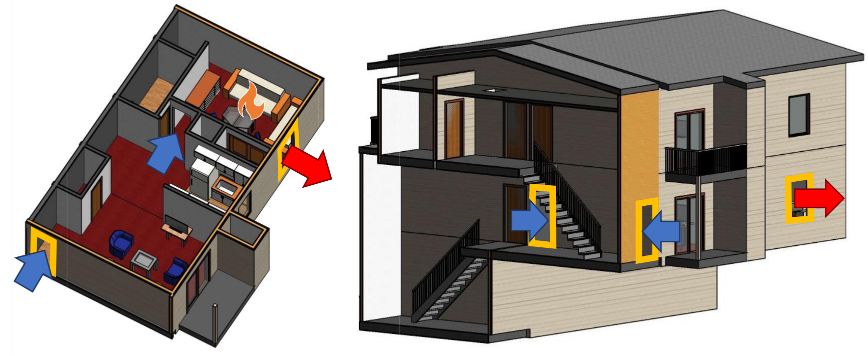
(a) Prior to Firefighter Intervention



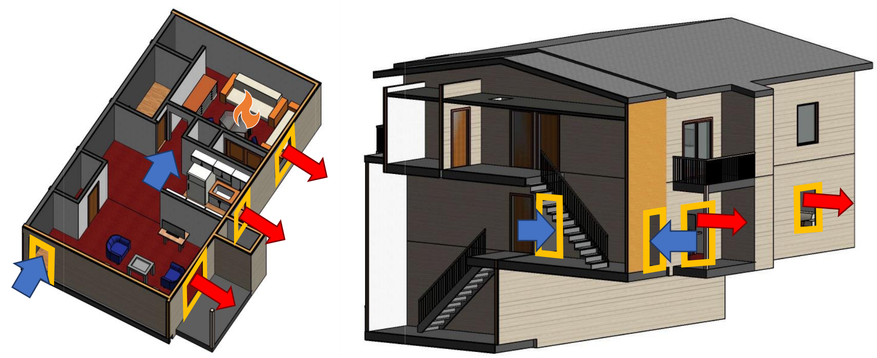
(b) Immediately After Opening the Apartment Door

Figure 3.80: Changes in flow during Experiment 2B prior to suppression. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

Air flow from the fan positioned outside of the breezeway door led to a build up of pressure in the stairwell, leading to unidirectional intake at the breezeway and apartment doors and unidirectional exhaust at the fire room window (see Figure 3.81a). The kitchen window and living room sliding glass door were opened about 7 min. later, providing additional exhaust vents (see Figure 3.81b).



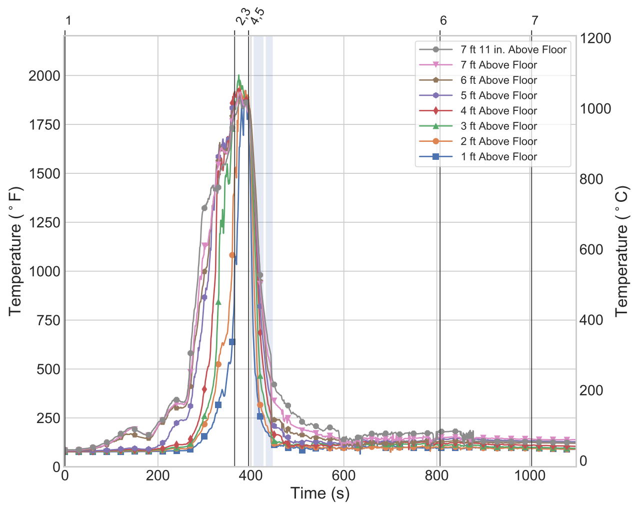
(a) After Starting PPA and Interior Suppression



(b) After Ventilating the Kitchen and Living Room

Figure 3.81: Changes in flow during Experiment 2B during suppression and post-knockdown. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

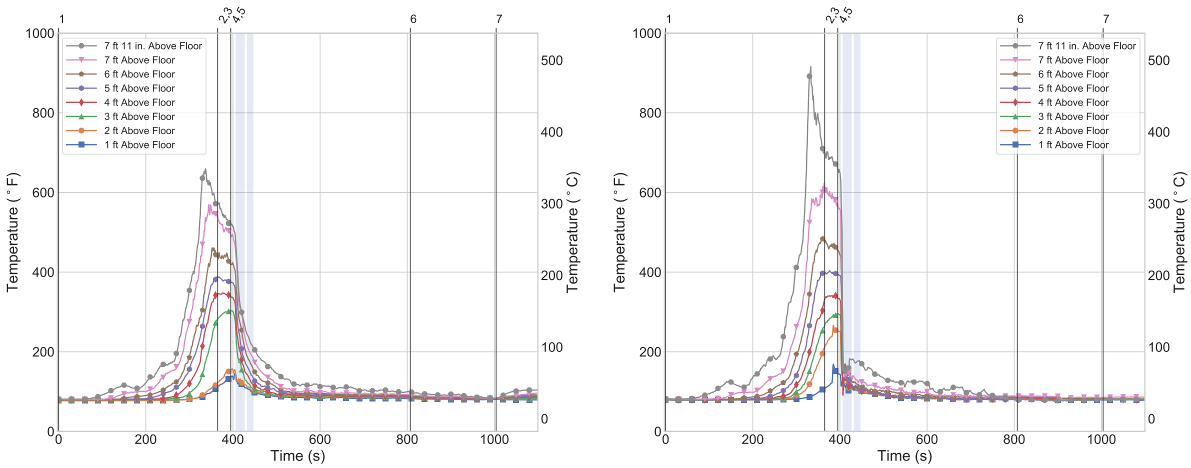
The time histories of the fire room temperatures are presented in Figure 3.82. The temperature near the bedroom ceiling began to increase at 120 s (2:00) post-ignition. Temperatures near the floor were slower to respond as hot gases filled the room from the top down, and began increasing at around 265 s (4:25). At approximately 365 s (6:05), temperatures at all elevations exceeded 1100 °F, indicating flashover. The peak temperatures ranged between 1700 °F, 1 ft above the floor and 2000 °F, 1 in. below the ceiling. Fire department intervention began shortly after the bedroom transitioned to flashover. The bedroom temperature immediately responded to suppression at 395 s (6:35), with temperatures at all elevations falling below 200 °F within 150 s.



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

Figure 3.82: Fire room (bedroom) temperatures for Experiment 2B. Blue shaded regions indicate time and duration of water flow.

The temperatures in the kitchen and living room of the fire room increased during the fire growth and post-flashover stages, then dropped in response to suppression (see Figure 3.83). Temperatures near the ceiling in both rooms began increasing around 70 s (1:10) after ignition. The peak temperatures occurred between 333 s (5:33) and the start of suppression at 395 s (6:35). Between 1 ft above the floor and 1 in. below the ceiling, the peak temperatures ranged from 170 °F to 915 °F in the kitchen and from 145 °F to 660 °F in the living room. Temperatures in both rooms responded immediately to the start of suppression. The kitchen temperatures decreased faster because the kitchen's proximity to the fire made it a larger focus for immediate water application from the suppression crew. Temperatures continued to decrease after the initial water flows.

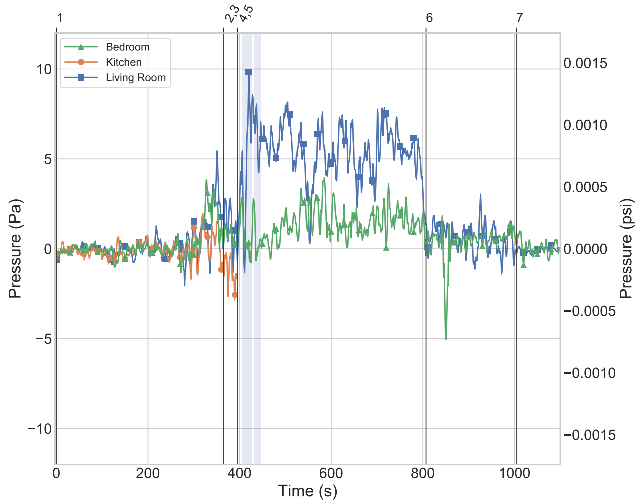


(a) Living Room (b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

Figure 3.83: Living room and kitchen temperatures for Experiment 2B. Blue shaded regions indicate time and duration of water flow.

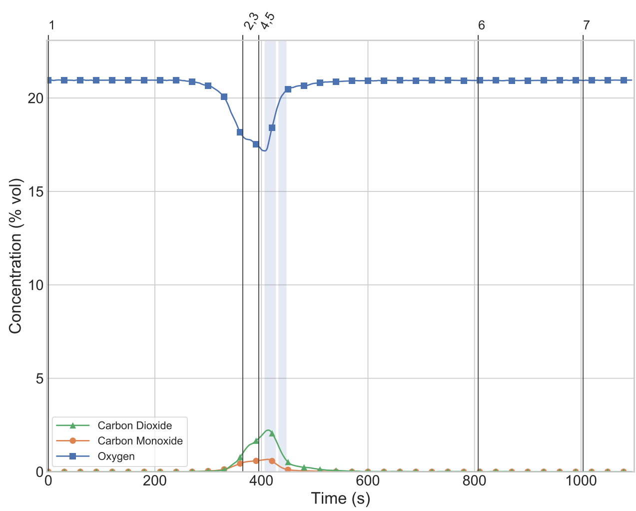
The time histories of the fire apartment pressures are presented in Figure 3.84. The open window in the bedroom (fire room) from the start of the experiment allowed combustion gases to exhaust to the environment. The open window limited the build-up of pressure in the fire apartment during the fire growth and fully developed stages. As a result, the pressure in the bedroom remained near 0 Pa for the entire experiment, and the living room and kitchen pressures remained near 0 Pa until the start of PPA. The pressure tap in the kitchen was impacted during the initial water flow during suppression, so data from that sensor after the start of suppression is omitted. PPA maintained elevated pressure in the living room of approximately 5 Pa until the living room sliding glass door and kitchen window were opened. Ventilation of the kitchen and living room at 807 s (13:27) allowed additional air exchange from the fire apartment to outside, reducing the pressure in the living room to ambient conditions.



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

Figure 3.84: Fire apartment pressures for Experiment 2B. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

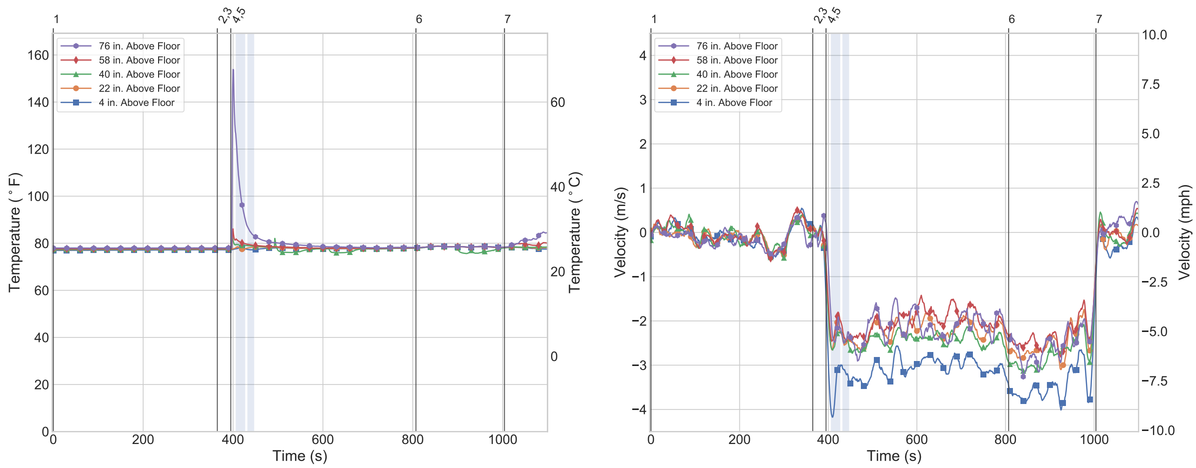
Gas concentrations were measured in the living room of the fire apartment (see Figure 3.85). Gas concentrations began to change in response to the fire growth at around 285 s (4:45). The O_2 concentration decreased to a minimum of 17.1% at 408 s (6:48). At the same time, the CO and CO_2 concentrations reached maximums of 0.7% (7000 ppm) and 2.2%, respectively. These peak values occurred shortly after the start of suppression at 395 s (6:35). Afterward, the gas concentrations quickly returned to ambient conditions as PPV increased airflow throughout the compartment. Ambient conditions were achieved at approximately 550 s (9:50).



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

Figure 3.85: Living room gas concentrations for Experiment 2B. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened at 395 s (6:35) post ignition to allow for the suppression crew to the enter the apartment. PPA began 2 s later as fan flow was initiated at the exterior door. Figure 3.86 shows the temperatures and velocities recorded at the fire apartment door. After the apartment door was opened, temperature at the top sensor rose to 155 °F, then quickly returned to ambient conditions as PPA limited the production of combustion products and moved fresh air into the apartment. Flow was unidirectional at 1.5 m/s (3 mph) to 4 m/s (9 mph) into the apartment. The gas velocities remained in that range until PPA ended at 1004 s (16:44), when they slowed to 0 m/s.

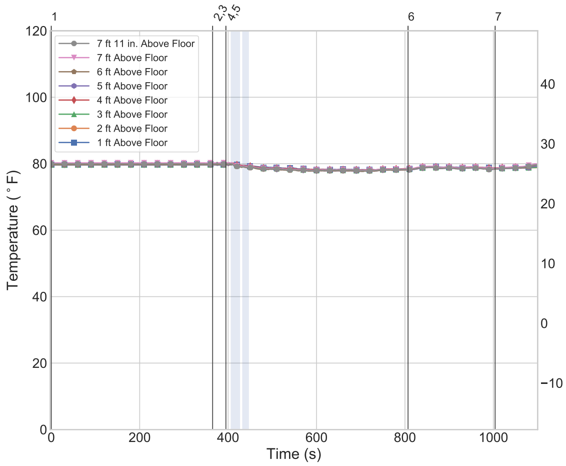


(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

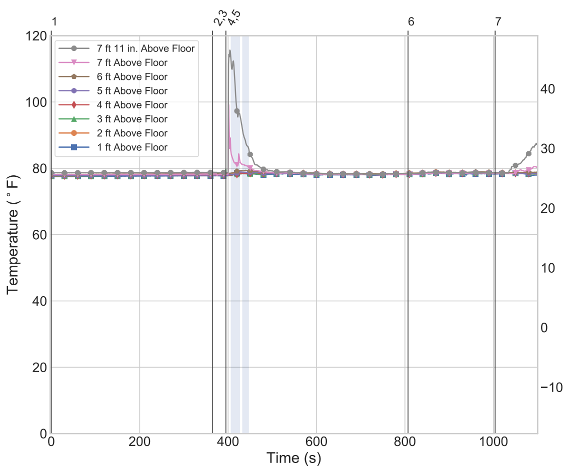
Figure 3.86: Temperatures and velocities at fire apartment (Apartment A) door for Experiment 2B. Blue shaded regions indicate time and duration of water flow.

With the exception of the first floor, the temperatures in the stairwell remained ambient and steady (about 80 °F) for the duration of the experiment (see Figure 3.87). The exception on the first floor was a temperature increase when the apartment door was opened, which released smoke into the stairwell. The temperatures 1 in. and 1 ft below the ceiling reached peaks of 115 °F and 100 °F, respectively. Temperatures measured below 7 ft above the floor did not increase as a result of the apartment door opening. The temperatures at 1 in. and 1 ft below the ceiling returned to ambient conditions that coincided with the start of PPA. After PPA ended at 1004 s (16:44), temperatures near the ceiling on the first floor recovered slightly as the remaining smoke in the structure began to recirculate, but they did not exceed 90 °F.

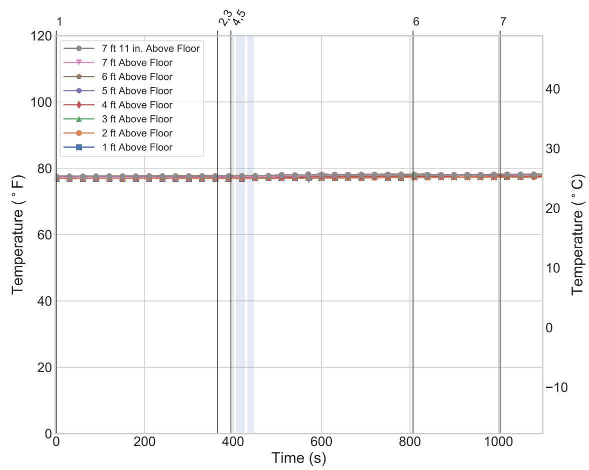


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004



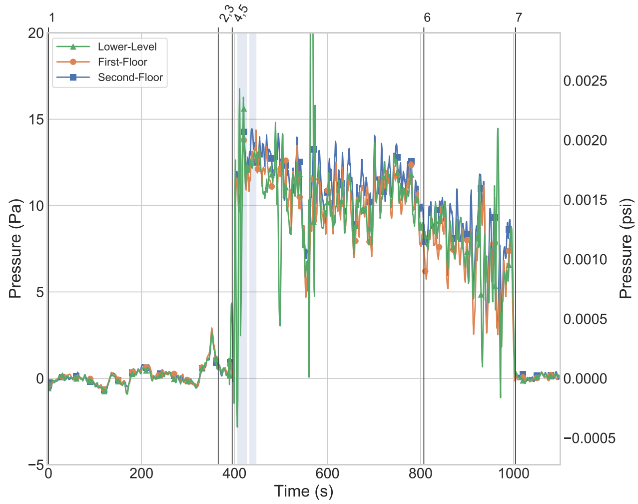
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.87: Stairwell temperatures for Experiment 2B. Blue shaded regions indicate time and duration of water flow.

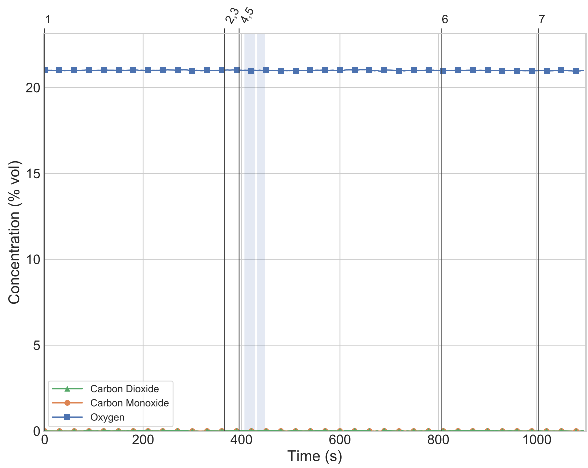
Pressures in the stairwell remained near ambient conditions until the start of PPA (see Figure 3.88). Pressures then increased to approximately 10 Pa in all levels of the stairwell until the living room sliding glass door and kitchen window were opened. Ventilating the kitchen and living room allowed for a greater flow path through the fire apartment, thereby reducing the pressure in the stairwell. The stairwell pressures then ranged from 5 Pa to 10 Pa until PPA ended at 1004 s (16:44), when they returned to ambient conditions.



	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

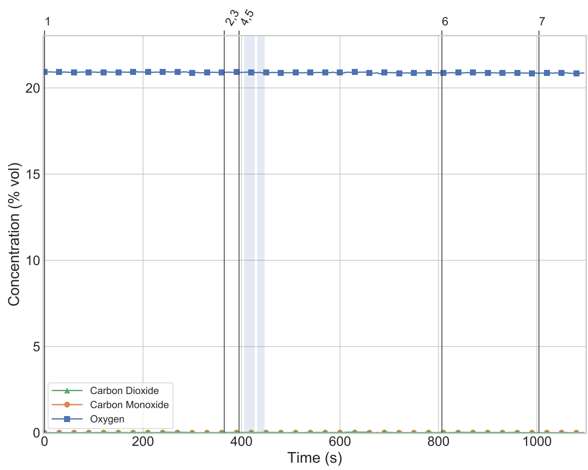
Figure 3.88: Stairwell pressures for Experiment 2B. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The gas concentrations in the stairwell remained near ambient conditions throughout the experiment (see Figure 3.89). The PPA limited smoke entering the stairwell from the fire apartment.

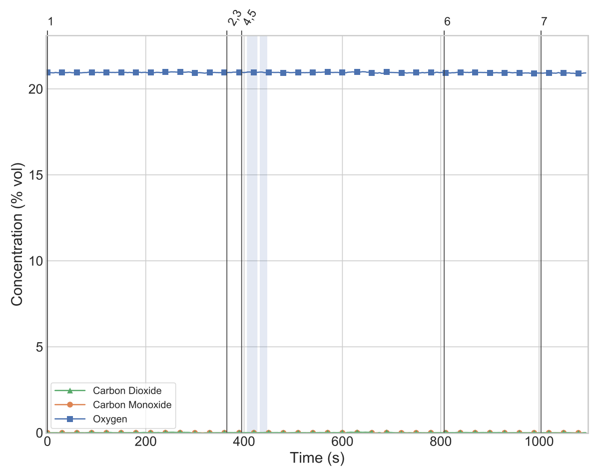


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004



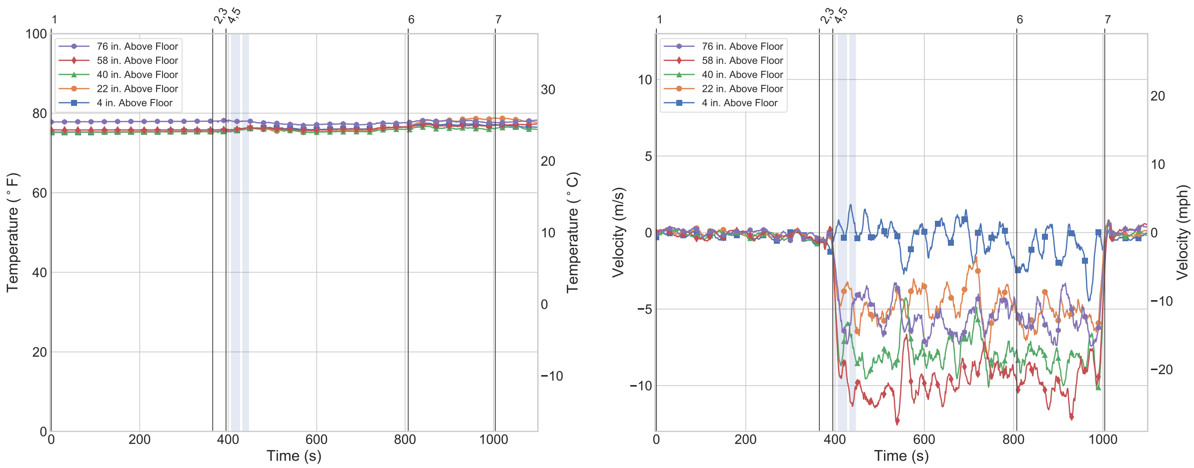
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.89: Stairwell gas concentrations for Experiment 2B. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The temperatures and velocities recorded at the exterior breezeway door are shown in Figure 3.90. PPA began at 397 s (6:37), which lead to unidirectional flow into the structure. The flow was fastest near the center of the door, where the velocity at the 58 in. elevation was approximately 10 m/s (22 mph). At the 22 in., 40 in., and 76 in. elevations, the velocities ranged from 5 m/s (11 mph) to 8 m/s (18 mph) into the structure. The flow was slowest at the 4 in. elevation, which generally sat around 0 m/s (0 mph). The velocities through the exterior door remained steady throughout PPA, and returned to 0 m/s at all elevations after PPA ended. The temperature at the exterior door reflected ambient conditions (about 80 °F) throughout the experiment.



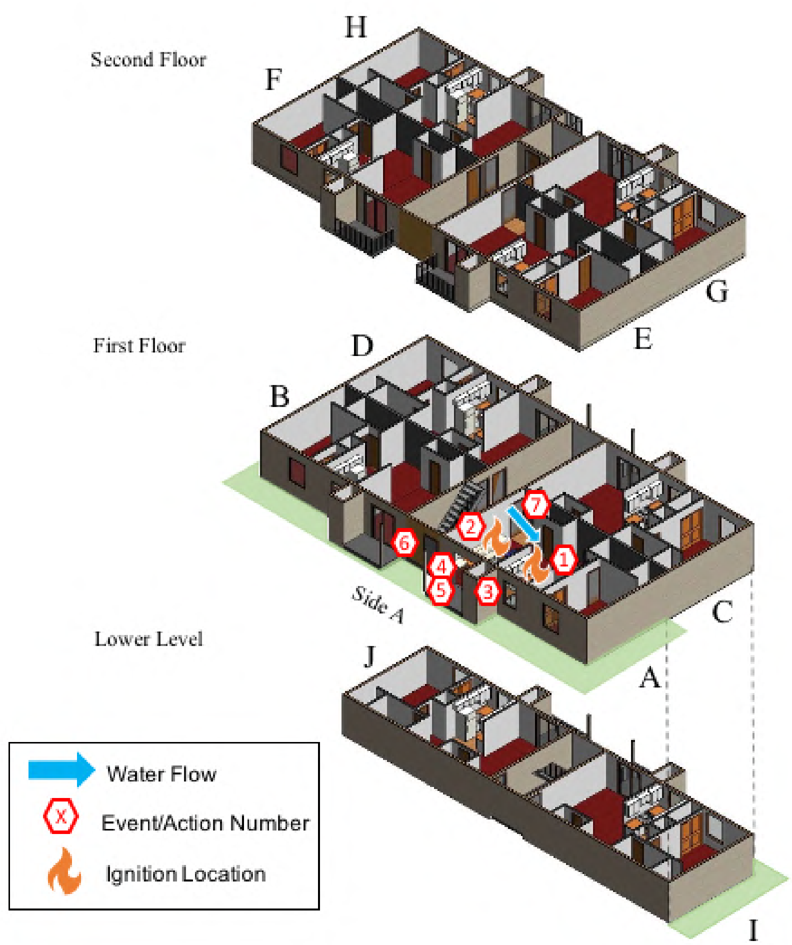
(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Flashover in bedroom	365
3	Open exterior door	372
4	Open apartment door; flow-and-move to fire room	395
5	Begin positive pressure attack	397
6	Ventilate kitchen and living room	807
7	End positive pressure attack	1004

Figure 3.90: Exterior door temperatures and velocities for Experiment 2B. Blue shaded regions indicate time and duration of water flow.

3.8 Experiment 3A – First-Floor Apartment Fire with Interior Suppression

Experiment 3A was conducted in Apartment A of 1974 Kimberly Village Lane SE, and it was designed to evaluate the use of interior suppression for a fire originating in the kitchen and living room of a first-floor apartment. Prior to ignition, half of the living room sliding glass door was open, the interior bedroom door was closed, and all other exterior windows and doors were closed, including the fire apartment door and doors to other apartments within the structure. Three ventilation changes occurred during the fire's growth: The kitchen window failed, the lower half of the open sliding glass door was temporarily blocked by a fallen sheet of drywall, and the other half of the sliding glass door was vented by firefighters. Firefighter intervention included entry to the structure, followed by entry into the fire apartment and flow-and-move suppression into the fire compartment. At necessary times throughout the experiment, water was applied from the exterior to the eaves on the front side of the structure to limit exterior fire spread to the adjoining address. This exterior water application did not enter the fire apartment, nor did it have an impact on the study of interior fire suppression for this experiment. Figure 3.91 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition in kitchen	00:00	0
2	Ignition in living room	10:00	600
3	Kitchen window failed	11:49	709
4	Open sliding glass door blocked by fallen drywall (60 s duration)	13:50	830
5	Vent other half of sliding glass door	16:09	969
6	Open exterior door	16:39	999
7	Open apartment door; begin interior suppression	17:11	1031

Figure 3.91: Time and sequence of actions and events for Experiment 3A.

The experimental volume included all areas of the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (IR and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.92 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

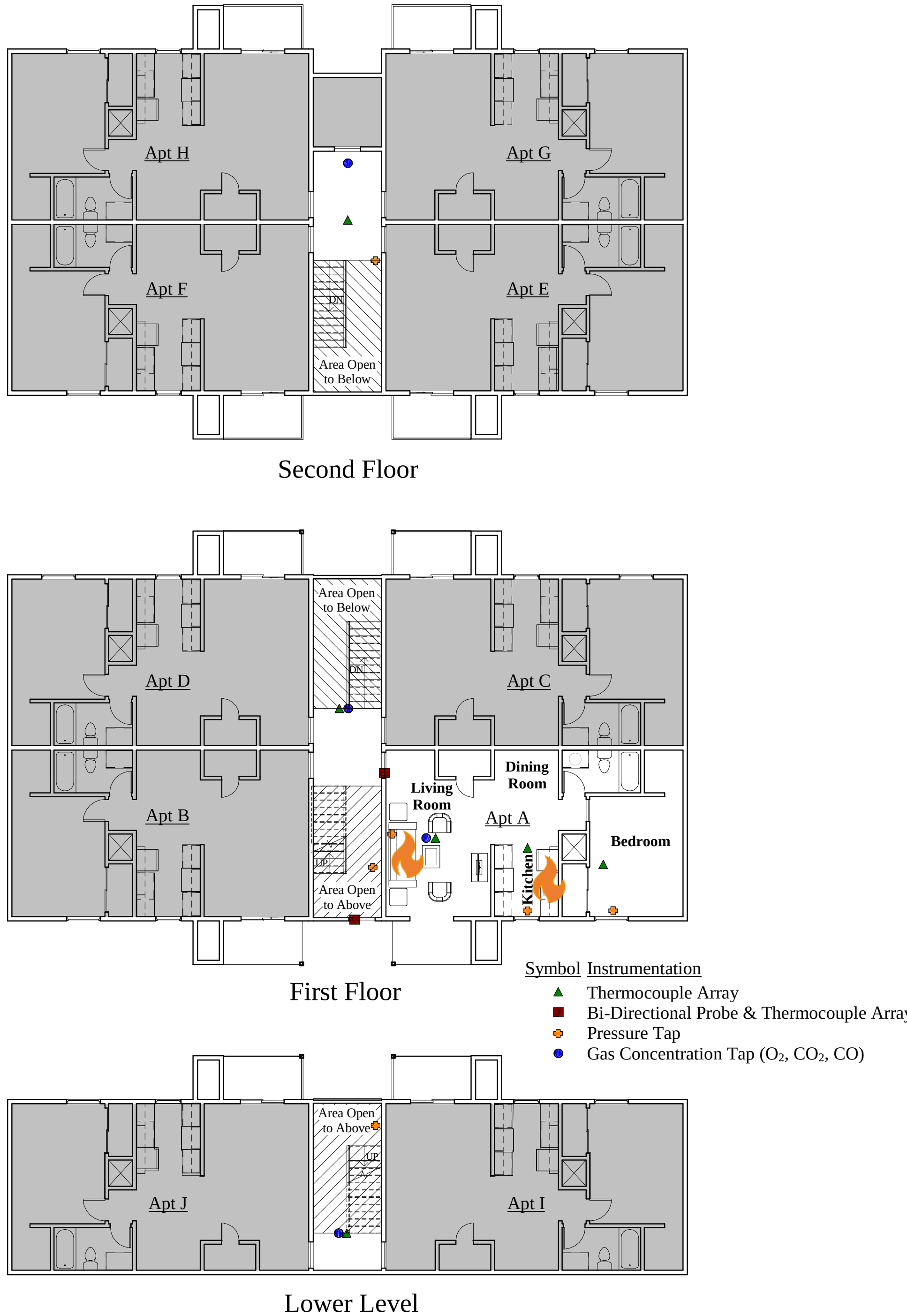


Figure 3.92: Instrumentation locations in Experiment 3A.

The kitchen and living room were furnished with the fuel loads described and photographed in Section 2.5. The bedroom was not furnished.

The fire in Experiment 3A was ignited via electric matches in small, plastic waste containers placed on the kitchen counter and on the floor next to the kitchen cabinets (t = 0 s). A smoke layer formed throughout the fire apartment, and smoke began showing out of the open living room sliding glass door at approximately 400 s. Figure 3.93a shows the fire spreading to the end of the kitchen cabinets at 600 s (10:00), when a second ignition was initiated by an electric match placed next to the arm of the sofa in the living room. Soon after, flames from the kitchen began extending into the living room at 650 s (10:50, shown in Figure 3.93b). The flame extension from the kitchen to living room lasted until approximately 686 s (11:26) as oxygen in the living room became limited due to the growth from the sofa fire.

(a) Interior Conditions at Time of Second Ignition (600 s)

(b) Flame Extension from Kitchen to Living Room (663 s)

Figure 3.93: Images of the fire apartment interior during fire growth in Experiment 3A.

The kitchen window failed 20 s later at 709 s (10:50), with flames showing immediately thereafter (see Figure 3.94a). The fire in the kitchen extended out of the broken kitchen window and continued to spread up the exterior wall, past the second-floor kitchen window and to the eave line above. At 840 s (14:00), exterior water was applied to the eave for 10 s to limit exterior fire spread to the adjoining address. Figure 3.94b shows an image of the exterior fire spread immediately prior to water application.

(a) Kitchen Window Failing (709 s) (b) Prior to Exterior Water Application (840 s)

Figure 3.94: Images of conditions viewed from the side A exterior in Experiment 3A as the kitchen window failed and prior to exterior water application.

In the living room, approximately 10 s prior to the exterior water application, a piece of drywall from the living room fell and blocked the lower half of the open sliding glass door. The fallen drywall was cleared by a firefighter about 60 s later (see Figure 3.95).

(a) Fallen Drywall Blocking the Sliding Glass Door (b) After Drywall was Broken by a Firefighter

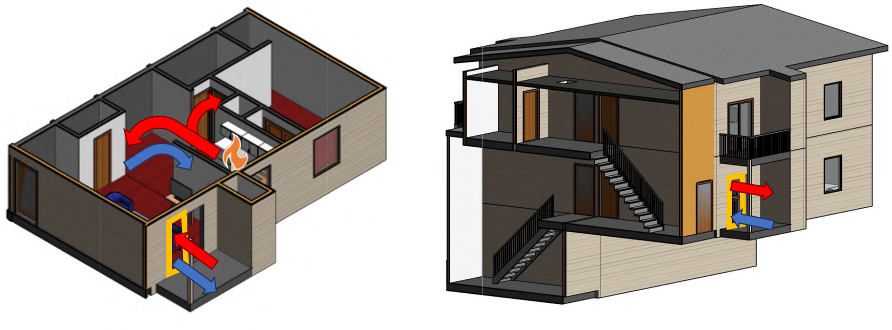
Figure 3.95: Images of drywall that fell, blocking the open living room sliding glass door in Experiment 3A.

During this period, the smoke layer in the living room descended to the floor. A firefighter broke the remaining half of the living room sliding glass door to provide additional ventilation at 969 s (16:09). The fire in the living room grew in response to the additional ventilation, and flames began extending out of the sliding glass door and engulfing the second-floor balcony within 10 s of it being broken. At the same time, the fire extending out of the kitchen window began to re-spread by traveling up the exterior wall and into the eaves (see Figure 3.96).

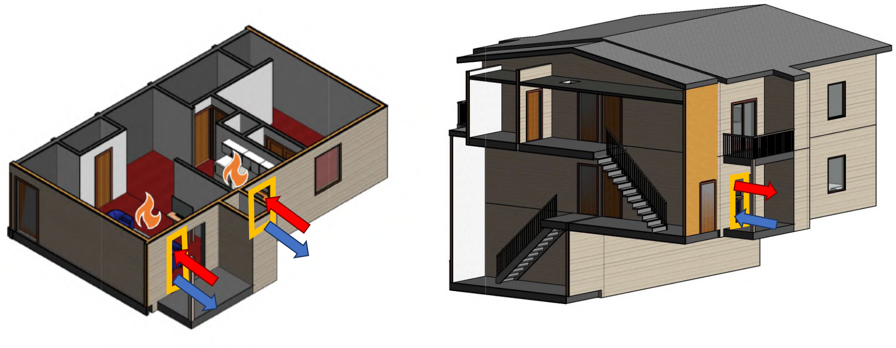
Figure 3.96: An image of fire growth prior to opening exterior door (999 s).

The exterior breezeway door was opened at 999 s (16:39). The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. Eight seconds after the suppression crew entered the structure, a separate crew applied exterior water for 7 s to the eaves above the kitchen window to slow the exterior fire spread. At approximately the same time as the exterior water application ended (1031 s (17:11)), the suppression crew opened the apartment door and began flowing 160 gpm from a 7/8 in. smooth bore nozzle operated in an O pattern and attached to 200 ft of 1 3/4 in. hoseline. Flames extended into the stairwell as soon as the apartment door was opened. The suppression crew flowed water from the apartment entrance for 25 s, then advanced into the apartment with the nozzle open and flowing. The initial interior suppression operation lasted 77 s, flowed 180 gallons of water, and successfully knocked down the fire. Concurrently with interior suppression, the exterior crew applied water for 13 s to the eaves above the living room sliding glass door to extinguish fire that had spread to the second-floor balcony. Any water flow after 450 s (7:30) was utilized during overhaul operations.

The flow paths of combustion gases and fresh air during the experiment are sketched in Figures 3.97 and 3.98. As the fire grew in the kitchen, high-temperature, lower density fire gases rose and began to fill the fire compartment from the top down. The kitchen was open to the living room, so the common space filled simultaneously. Once the hot gas layer reached the top of the open sliding glass door in the living room, gases began exhausting to the environment. At the same time, entrainment from the fire plume caused air to be drawn through the bottom of the sliding glass door into the apartment, which led to further fire growth (see Figure 3.97a). After the kitchen window failed, a new exhaust vent was created for the higher pressure combustions gases in the fire apartment. The gases exhausted out of the top portion of the sliding glass door and kitchen window while cooler, ambient air was entrained through the lower portion (see Figure 3.97b).



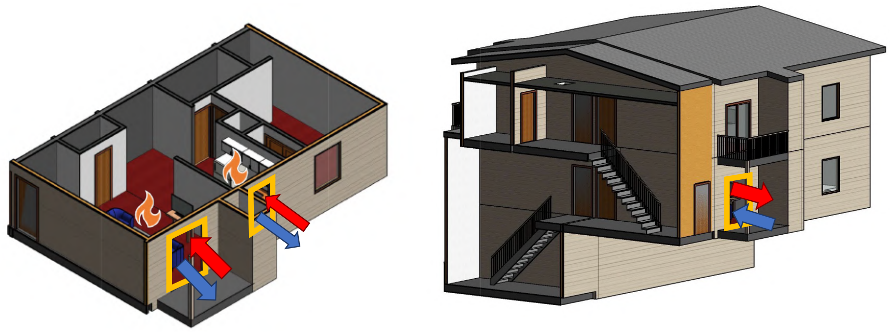
(a) Prior to Kitchen Window Failure



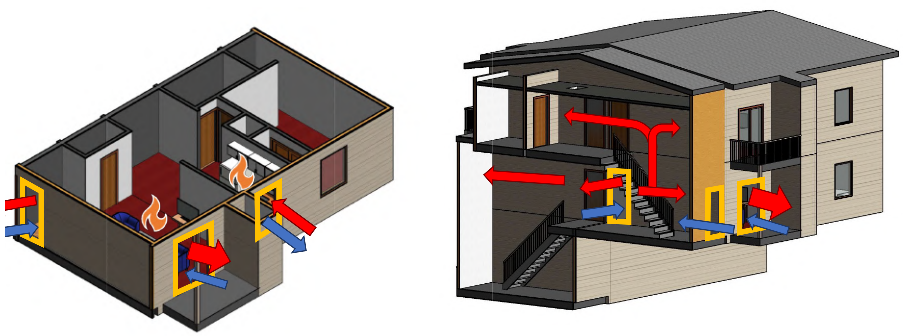
(b) After Kitchen Window Failed

Figure 3.97: Changes in flow during Experiment 3A due to kitchen window failure. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

The remaining half of the sliding glass door was vented about 4 min. after the kitchen failed. This increased both the exhaust of combustion gases from the fire compartment and the entrainment of cooler, ambient air to the fire (see Figure 3.98a). Firefighters entered through the exterior breezeway and fire apartment doors for interior suppression. Combustion gases flowed into the low-pressure stairwell through the top of the fire apartment door as cooler, ambient air was entrained at the bottom (see Figure 3.98b). Firefighters knocked down the fire, which stopped the production of gases, and the structure was naturally ventilated.



(a) After Venting Second-Half of Sliding Glass Door



(b) After Firefighter Entry and Interior Suppression

Figure 3.98: Changes in flow during Experiment 3A due to firefighter intervention and suppression. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

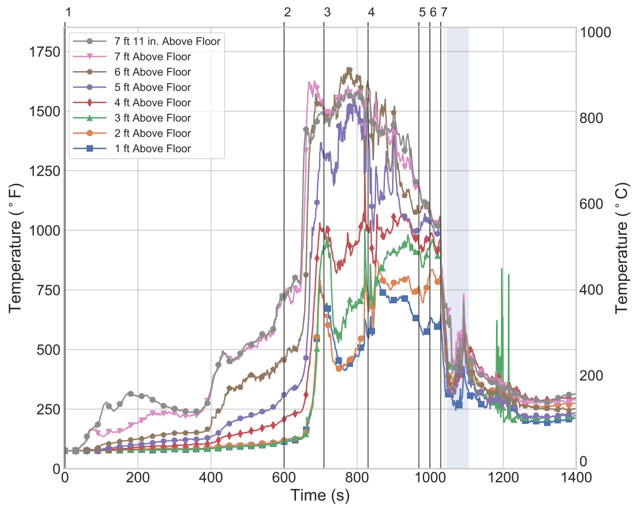
It is important to note that the fire burned for approximately 200 s without a portion of ceiling. The wood floor-joists charred and the metal gusset plates expanded and warped, weakening the floor/-ceiling assembly. After suppression ended and ventilation of the apartment was complete, crews noticed the ceiling joists of the fire apartment were sagging. Figure 3.99a documents the charred, sagging ceiling, while Figure 3.99b documents the warped gusset plates in the floor/ceiling assembly. Crews immediately exited the structure and access to the second-floor exposure apartment was limited.

(a) Sagging Ceiling (b) Warped Gusset Plate

Figure 3.99: Fire damage to the living room ceiling during Experiment 3A after failure of the drywall ceiling.

The time histories of the kitchen temperatures are presented in Figure 3.100. The temperature near the kitchen ceiling began to increase 30 s post-ignition. Prior to the second ignition in the living room, kitchen temperatures ranged from 110 °F 1 ft above the floor to 725 °F 1 in. below the ceiling. Temperatures at all elevations in the kitchen increased more rapidly as the living room fire grew. The kitchen window failed at 709 s (11:49). At this time, kitchen temperatures ranged from 725 °F 1 ft above the floor to 1520 °F 1 ft below the ceiling.

The kitchen temperatures stratified after the window failed, with temperatures at 5 ft and above exceeding 1500 °F and temperatures below 5 ft remaining below 1000 °F. The open living room sliding glass door became an intake and exhaust (bi-directional flow), and the kitchen window became a second exhaust to the flow path between the living room and kitchen. Cool air was entrained low into the living room sliding glass door, which provided oxygen to the fire. The higher temperature, higher pressure buoyant gases exhausted to the low-pressure exterior through both the top portion of the living room sliding glass door and kitchen window. This behavior was steady until the drywall from a portion of the living room ceiling fell, blocking the inlet air from the open living room sliding glass door and causing the fire to become ventilation-limited. This contributed to the kitchen temperatures beginning to decline. In an attempt to allow more fresh air into the compartment to support fire growth, the remaining half of the sliding glass door was vented. While temperatures below 4 ft in the kitchen began to rise ($\approx$ 50 °F), the higher elevations continued to decrease until the start of interior suppression at 1031 s (17:11). Prior to suppression, the kitchen temperatures ranged from 595 °F 1 ft above the floor to about 1050 °F near the ceiling. Interior suppression caused the kitchen temperatures to drop below 500 °F at all elevations as the fire was knocked down, and then continue decreasing slowly toward ambient conditions thereafter.

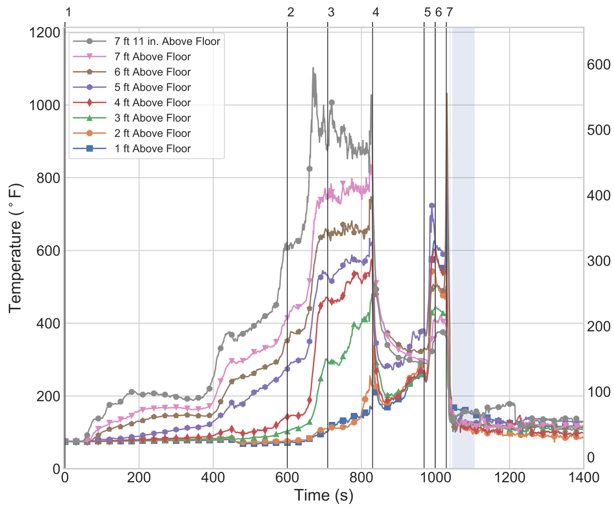


	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031

Figure 3.100: Kitchen temperatures for Experiment 3A. Blue shaded regions indicate time and duration of water flow.

During the growth stage of the kitchen fire, temperatures in the living room behaved similarly to those in the kitchen, but at lower temperatures (see Figure 3.101). The temperatures near the living room ceiling began to increase 60 s post ignition, and continued to increase through the secondary ignition in the living room. The living room temperatures began to stratify between 4 ft and 5 ft above the floor due to the fresh air entrained near the floor through the open sliding glass door. After ignition in the living room at 600 s (10:00), temperatures at 3 ft and above increased at a faster rate compared to the lowest thermocouples, which were cooled by the intake air. Temperatures above 3 ft continued to increase until the kitchen window failed at 709 s (11:49), after which they became steady, with temperatures ranging between 285 °F 3 ft above the floor and 825 °F 1 in. below the ceiling. The 1 ft and 2 ft temperatures remained under 200 °F due to the air entrainment.

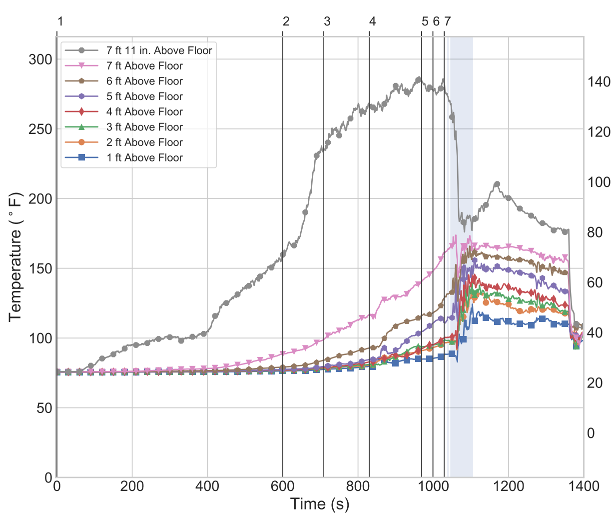
At about 830 s (13:50), when the piece of drywall fell from the living room ceiling and blocked the lower half of the sliding glass door, temperatures fell below 400 °F. The drywall limited fresh air entering the apartment and contributed toward the fire becoming ventilation-limited. The fallen drywall was cleared about 1 min. later. The living room temperature remained below 400 °F until the remaining half of the sliding glass door was broken at 969 s (16:09) to allow additional ventilation. The fire grew in response to the additional ventilation, with flames extending out the sliding glass door within 10 s. Temperatures at all elevations in the living room increased by more than 50 °F in less than 20 s. The effect was greatest below 6 ft, where temperature increased by more than 200 °F in the same time. When the apartment door was opened at 1031 s (17:11), the living room temperatures ranged between 370 °F 1 in. below the ceiling and 590 °F 5 ft above the floor. Temperatures at all elevations in the living room peaked in response to the apartment door being opened as a new source of fresh air became available to the fire. The temperatures then immediately dropped below 200 °F in response to suppression, and continued to decrease toward ambient conditions thereafter.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior doors	999
7	Open apartment door; begin interior suppression	1031

Figure 3.101: Living room temperatures for Experiment 3A. Blue shaded regions indicate time and duration of water flow.

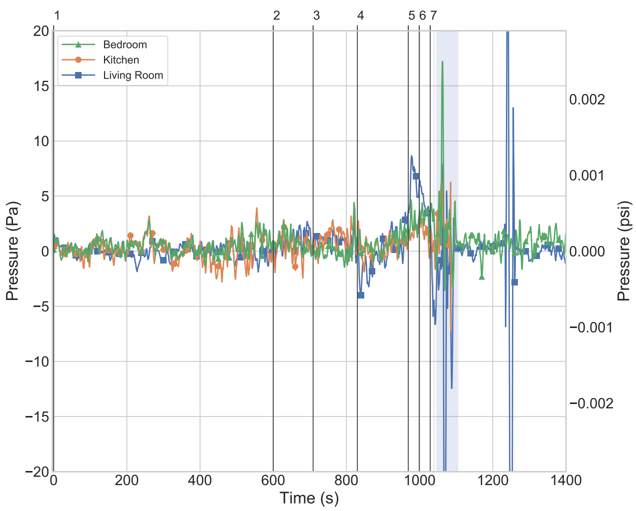
Temperatures in the bedroom of the fire apartment remained much lower than the kitchen and living room due to the closed bedroom door (see Figure 3.102). Smoke leaking through the top of the bedroom door led to a rise in the temperature 1 in. below the ceiling. The temperatures peaked near the start of suppression, between 965 s (16:05) and 1100 s (18:20). The peak temperature 1 in. below the ceiling was 285 °F. Below that height, the peak temperatures ranged between 120 °F and 185 °F. Temperatures in the bedroom dropped at approximately 1380 s as the bedroom was vented, which allowed the built-up heat to escape.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031

Figure 3.102: Bedroom temperatures for Experiment 3A. Blue shaded regions indicate time and duration of water flow.

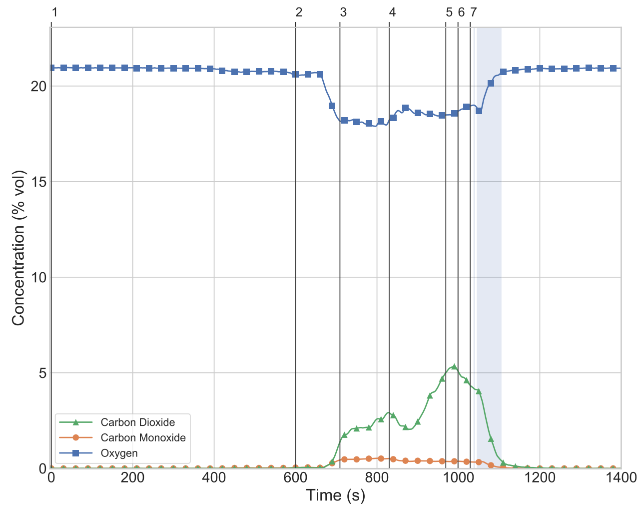
The time histories of the fire apartment pressures are presented in Figure 3.103. The open sliding glass door in the living room was a low-pressure exhaust for the duration of the experiment, which limited the build-up of pressure in the fire apartment. Pressures in each room of the fire apartment remained near ambient conditions. At 969 s (16:09), when the other half of the living room sliding glass door was vented, the living room pressure increased as a result of the fire growth. The pressure reached a peak of 9 Pa at 979 s (16:19), and remained positive until the fire apartment door was opened and interior suppression began. During suppression, the cooling led to gas contraction, which resulted in negative pressures. The kitchen pressure sensor was impacted by water, so data from that sensor is omitted thereafter. The living room and bedroom pressures returned to 0 Pa at the end of interior suppression.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031

Figure 3.103: Fire apartment pressures for Experiment 3A. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

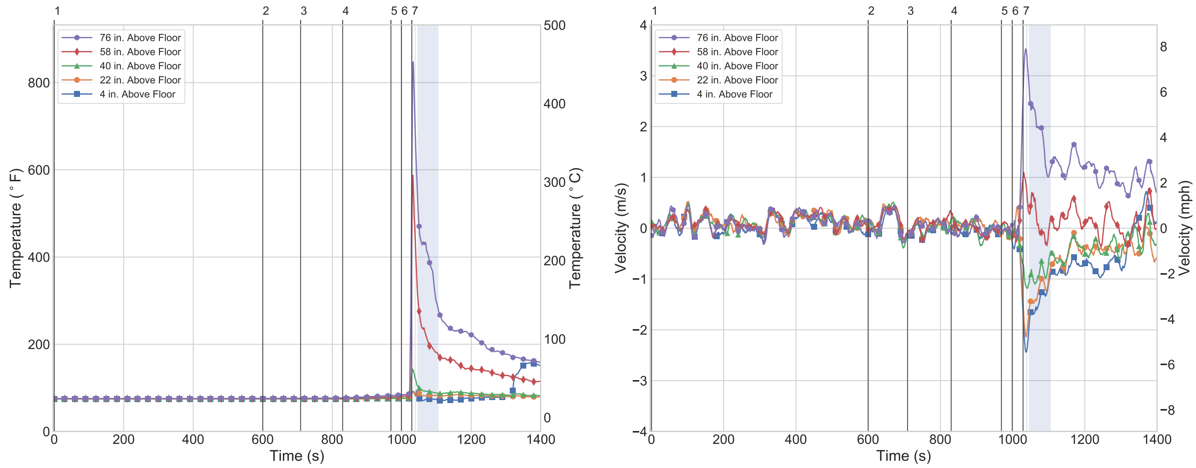
Gas concentrations in the living room of the fire apartment remained ambient until approximately 650 s (10:50) post kitchen ignition (50 s post living room ignition, see Figure 3.104). O_2 concentration decreased to 17.9% while CO_2 and CO concentrations increased to 2.9% and 0.6% (6000 ppm) by 830 s (13:50). When the drywall fell in front of the living room sliding glass door and the fire began to decay, gas concentrations slightly improved. Oxygen rose to 18.9% O_2 and carbon dioxide and carbon monoxide fell to 2.0% and 0.4% (4000 ppm), respectively. Afterward, the O_2 and CO levels remained steady, while the CO_2 level increased to a peak of 5.3% at 987 s (16:27) as a result of the fire growth. Interior suppression began at 1031 s (17:11), which returned the gas concentrations to near ambient levels by the end of water flow. Ambient conditions were achieved by 1100 s (18:20).



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031

Figure 3.104: Living room gas concentrations for Experiment 3A. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The fire apartment door was opened 1031 s (17:11) post-ignition to allow for the suppression crew to the enter. Flames immediately extended into the stairwell from the apartment. Figure 3.105 shows the temperatures and velocities recorded at the fire apartment door. After the apartment door was opened, temperature at the 76 in. and 58 in. elevations increased to 850 °F and 590 °F, respectively. Gases at those elevations exhausted out of the apartment at approximately 3.5 m/s (8 mph) at the 76 in. elevation and 1 m/s (2 mph) at the 58 in. elevation. At the 40 in. elevation and below, gas initially flowed into the apartment as the pre-existing vents in the apartment acted as the predominant exhaust vents for the higher pressure fire room gases. The peak velocities into the apartment were between 1 m/s (2 mph) 40 in. above the floor and 2.5 m/s (6 mph) 4 in. above the floor. Following suppression, gas flow at all elevations through the door slowed toward 0 m/s because the production of combustion gases had stopped and pressures dropped throughout the compartment. The thermocouple at the 40 in. elevation did measure an initial increase in temperature despite the inflow due to heat transfer from the hot gases exhausting through the doorway above the probe.

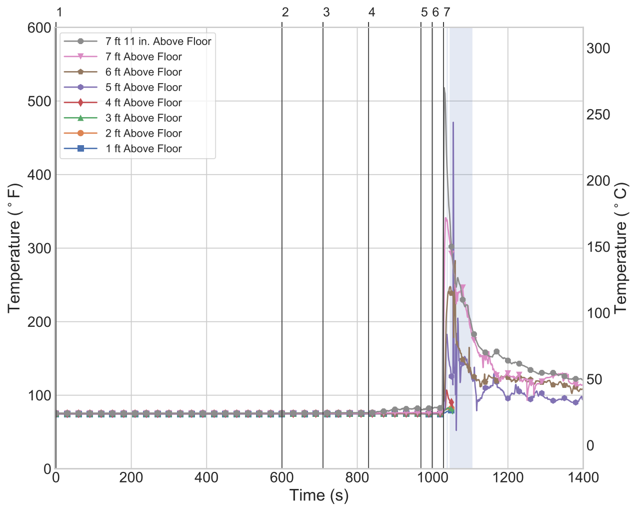


(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031

Figure 3.105: Temperatures and velocities at fire apartment (Apartment A) door for Experiment 3A. Blue shaded regions indicate time and duration of water flow.

Temperatures in the stairwell on the first floor remained ambient and steady (about 75 °F) until firefighters opened the fire apartment door (see Figure 3.106). Temperatures on the first floor increased in response to the smoke and flames extending from the fire apartment into the stairwell. Peak temperatures ranged between 520 °F 1 in. below the ceiling and 105 °F 4 ft above the floor. Thermocouples below 4 ft on the first floor did not measure an increase. The thermocouple arrays on the second floor and lower level were both damaged prior to firefighter entry. This was likely damage to the extension wires that ran from stairwell to the data acquisition hardware. As a result, those two locations were not included in this experiment.

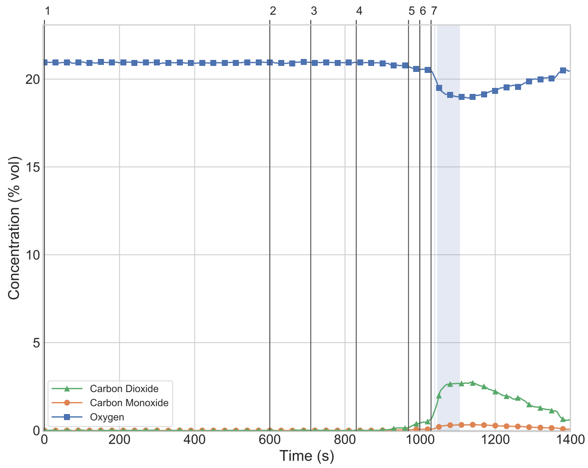


	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031

Figure 3.106: First-floor stairwell temperature for Experiment 3A. Blue shaded regions indicate time and duration of water flow.

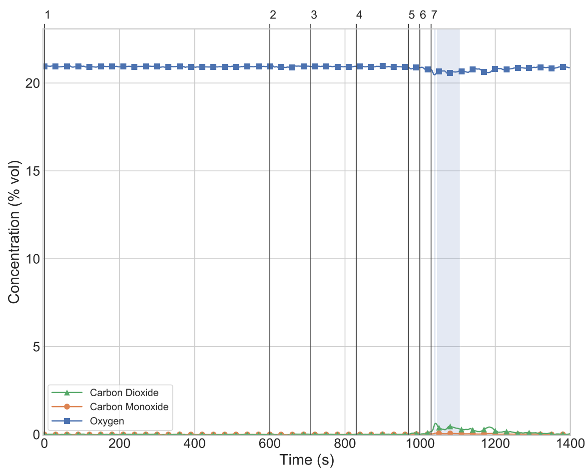
Stairwell pressures remained near ambient levels, between -2 Pa and 2 Pa for the duration of the experiment. The pressures did not respond noticeably to any fire changes or firefighter interventions.

Gas concentrations began to change on the second floor of the stairwell after firefighters opened the fire apartment door at 1031 s (17:11, see Figure 3.107). The buoyant, high-temperature combustion products filled the stairwell from the top down. The O_2 concentration decreased to a minimum of 19% while CO_2 and CO concentrations increased to maximums of 2.5% and 0.4% (4000 ppm) by 1100 s (18:20). Gas concentrations remained near ambient on the lower level and first floor of the stairwell because the smoke layer did not descend beyond the 4 ft level (measurement elevation) of the first floor.

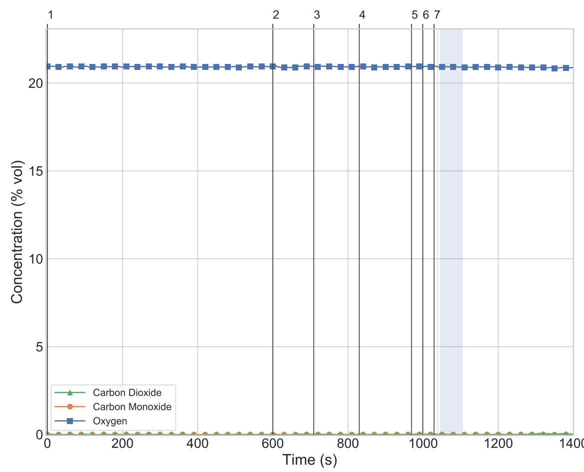


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	600
3	Kitchen window failed	709
4	Open sliding glass door blocked by fallen drywall	830
5	Vent other half of sliding glass door	969
6	Open exterior door	999
7	Open apartment door; begin interior suppression	1031



(b) First-Floor Stairwell

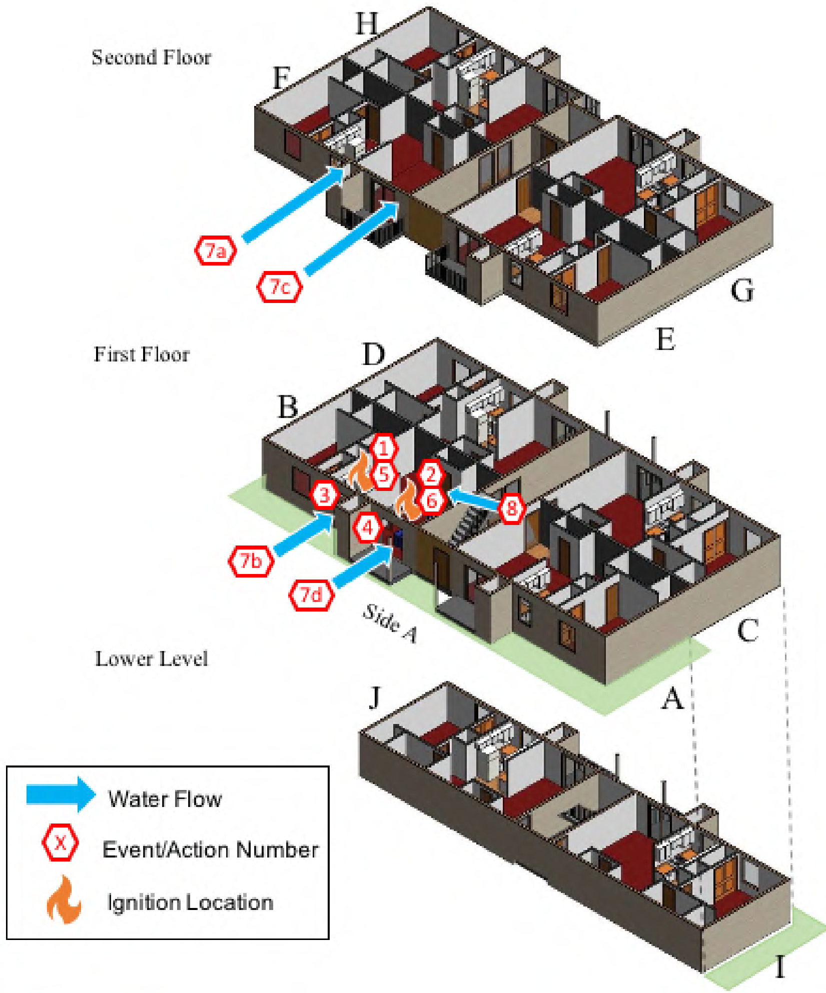


(c) Lower-Level Stairwell

Figure 3.107: Stairwell gas concentrations for Experiment 3A. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

3.9 Experiment 3B – First-Floor Apartment Fire with Exterior Fire Control

Experiment 3B was conducted in Apartment B of 1974 Kimberly Village Lane SE, and it was designed to evaluate the use of exterior fire control for a fire that originated in the kitchen and living room of a first-floor apartment. Prior to ignition, half of the living room sliding glass door was open, the interior bedroom door was closed, and all other exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. Firefighter intervention included venting the other half of the living room sliding glass door, followed by exterior fire control, entry to the fire apartment and follow-up interior suppression. Figure 3.108 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition in kitchen	00:00	0
2	Ignition in living room	07:00	420
3	Kitchen window failed	08:42	522
4	Vent other half of sliding glass door	09:49	589
5	Flashover in kitchen	10:32	632
6	Flashover in living room	11:54	714
7	Begin exterior fire control:		
	a) Exterior water to eave above kitchen for 9 s	12:48	768
	b) Exterior water into kitchen window for 10 s	12:57	777
	c) Exterior water to eave above living room for 4 s	13:15	795
	d) Exterior water into sliding door for 11 s	13:19	799
8	Open apartment door; begin interior suppression	13:45	825

Figure 3.108: Time and sequence of actions and events for Experiment 3B.

The experimental volume included the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.109 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

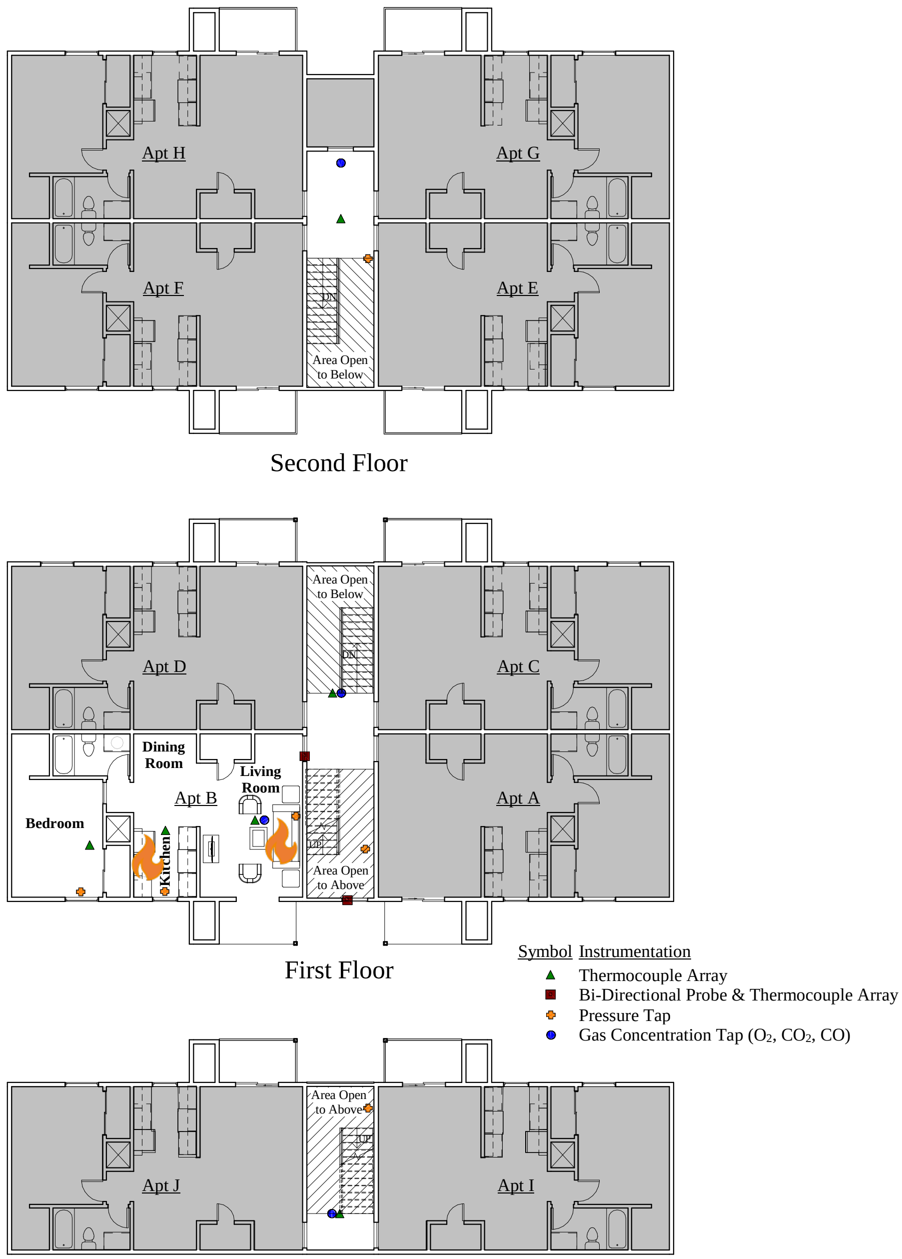


Figure 3.109: Instrumentation locations in Experiment 3B.

The kitchen and living room were furnished with the fuel loads described and photographed in Section 2.5.

The fire in Experiment 3B was first ignited via electric matches in two small, plastic waste containers; one was placed on the kitchen counter, and the other on the floor next to the kitchen cabinets (t = 0 s). A smoke layer formed throughout the apartment and smoke began to flow out of the living room sliding glass door at approximately 93 s. Figure 3.110a shows the fire extending from the kitchen to the living room at 420 s (7:00), when a second ignition was initiated by an electric match placed next to the arm of the sofa in the living room. The smoke layer descended to the apartment floor by around 500 s (8:20). Smoke became visible in the bedroom at about 440 s (7:20) through normal leakage around the closed door and began to accumulate in the enclosed space.

The kitchen window failed at 519 s (8:49) and firefighters broke the remaining half of the living room sliding glass door 70 s later, at 589 s (9:49). The fire grew in response to the additional ventilation. The kitchen transitioned to flashover at 632 s (10:32), followed by the living room at 711 s (11:51). Figures 3.110b and 3.110c show conditions on the exterior front of the structure at the times of each flashover. Fire also extended above the kitchen window and living room sliding glass doors to the floor and eave line above. Smoke and flames began to engulf the second-floor balcony.

(a) Interior Conditions at Time of Second Ignition (420 s)

(b) Exterior Conditions at Time of Kitchen Flashover (632 s)

(c) Exterior Conditions at Time of Living Room Flashover (711 s)

Figure 3.110: Images of the fire apartment during fire growth and flashover in Experiment 3B.

The suppression crew began to apply water from the exterior at 762 s (12:42), flowing 160 gpm from a 7/8 in. smooth bore nozzle attached to 200 ft of 1 3/4 in. hoseline. The first water application was to the eave line above the kitchen window (see Figure 3.111a). The nozzle firefighter swept the eaves for 9 s, then brought the stream down the side of the building, past the second floor kitchen window to the first-floor kitchen window. The hose stream was aimed through the first-floor kitchen window while the nozzle firefighter advanced forward toward the structure (see Figure 3.111b). As the nozzle firefighter reached the threshold of the window, the nozzle was manipulated to a half-bale position. Water was applied through the kitchen window for 10 s. The suppression crew then repositioned in front of the living room sliding glass door. The nozzle firefighter opened to a full-bale position and swept the hose stream across the second-floor balcony and eaves for 4 s (see Figure 3.111c), and then directed the hose stream into the living room through the sliding glass door (see Figure 3.111d). The hose stream was aimed at the living room ceiling at as steep of an angle as possible. Subsequently, the hose stream was deflected off of the lintel of the sliding glass door, providing additional distribution within the compartment. Water application in the living room lasted for 11 s. The total time for exterior water application was 37 s, resulting in 94 gallons of water flowed.

(a) Start of Water Application to Eaves Above Kitchen Window (768 s)

(b) During Water Application through Kitchen Window (Started at 777 s)

(c) Start of Water Application Above Living Room Sliding Glass Door (795 s)

(d) During Water Application through Living Room Sliding Glass Door (Started at 799 s)

Figure 3.111: Images of each stage of the side A exterior water application in Experiment 3B.

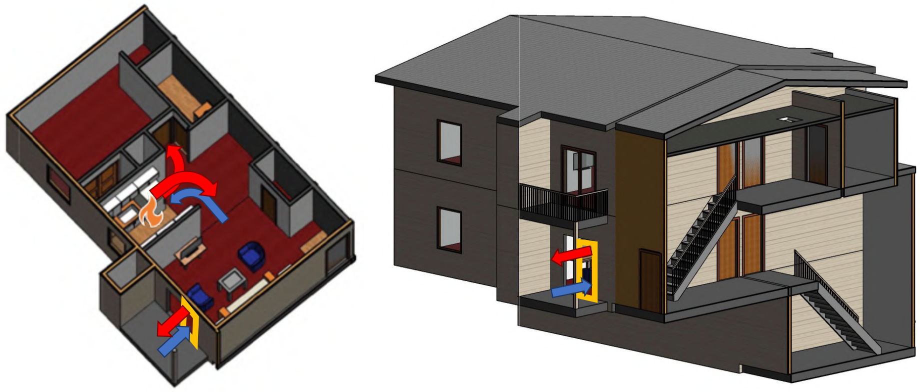
The suppression crew then opened the exterior breezeway door and proceeded to the fire apartment door. The fire apartment door was opened at 825 s (13:45), and the suppression crew immediately began flowing water and advanced into the apartment. The initial interior fire suppression lasted 29 s and flowed 91 gallons of water. Water flow after the initial interior fire suppression ended at 854 s (8:14) was utilized for overhaul operations.

During fire growth in the kitchen, the kitchen window naturally ventilated and flames began spreading upwards along the siding of the structure. As the fire ignited the vinyl siding and T1-11 sheeting, flames spread upwards, across the second-floor kitchen window and to the eave-line. The second-floor kitchen window failed from the heat transfer due to direct flame impingement. Flames spread into the apartment through the ventilated window and began to burn the kitchen cabinets of Apartment F. Figure 3.112a documents fire damage in the second-floor kitchen in Apartment F. Flames also reached the eave-line and began spreading laterally in both directions. The flames were allowed to grow for 244 s before exterior water was used to cool the siding, eaves and second-floor kitchen. Exterior water was successful in extinguishing flame spread into both the attic void space and second-floor kitchen. Figure 3.112b documents fire damage in the attic void space post knock down.

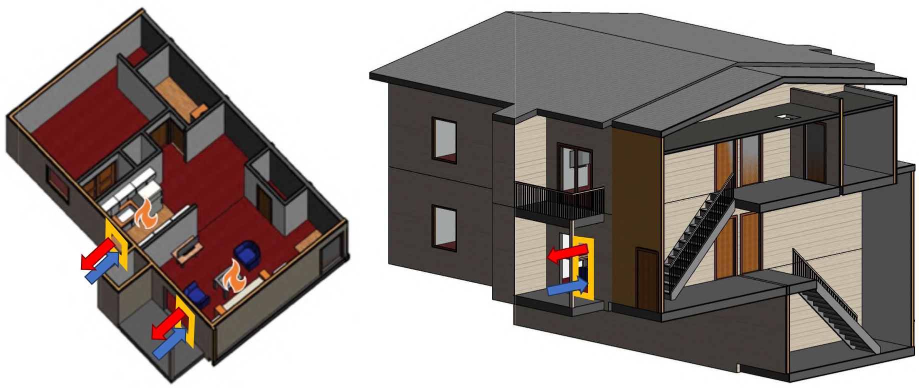
(a) Extension Damage to Second-floor Kitchen (b) Extension Damage to Attic Void Space

Figure 3.112: Fire damage in the second-floor kitchen and attic void space during Experiment 3B due to exterior fire spread.

The flow of combustion gases and fresh air during the experiment are sketched in Figures 3.113 and 3.114. As the fire grew in the kitchen, high-temperature, lower density fire gases rose and began to fill the fire compartment from the top down. The kitchen was open to the living room, so the common space filled simultaneously. Once the hot gas layer reached the top of the open sliding glass door in the living room, gases began exhausting to the environment. At the same time, entrainment from the fire plume caused air to be drawn through the bottom of the sliding glass door into the apartment (see Figure 3.113a). The kitchen window failed, which provided a new exhaust for the higher pressure gases. The gases exhausted out of the top portion of the sliding glass door and kitchen window while cooler, ambient air was entrained through the lower portion (see Figure 3.113b).



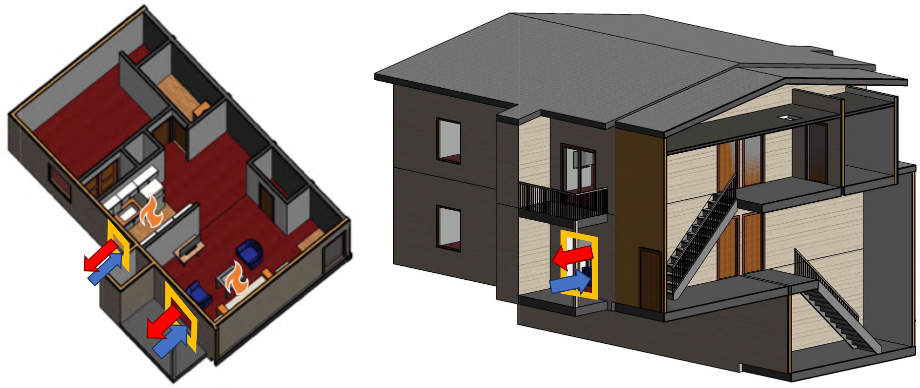
(a) Prior to Kitchen Window Failure



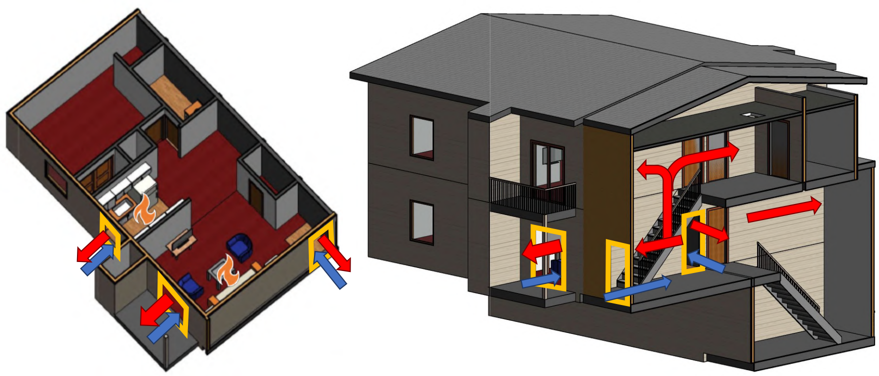
(b) After Kitchen Window Failed

Figure 3.113: Changes in flow during Experiment 3B due to kitchen window failure. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

The remaining half of the sliding glass door was vented about 60 s after the kitchen window failed. This increased both the exhaust of combustion gases from the fire compartment and the entrainment of cooler, ambient air to the fire. As a result, the fire compartment transitioned to flashover (see Figure 3.114a). Firefighters then began exterior fire control, followed by entry through the exterior breezeway and fire apartment doors to conduct interior suppression. Higher pressure gases from the apartment flowed into the enclosed stairwell through the top of the fire apartment door as cooler, ambient air was entrained at the bottom (see Figure 3.114b). Firefighters knocked down the fire, which stopped the production of combustion gases.



(a) After Venting Second-Half of Sliding Glass Door



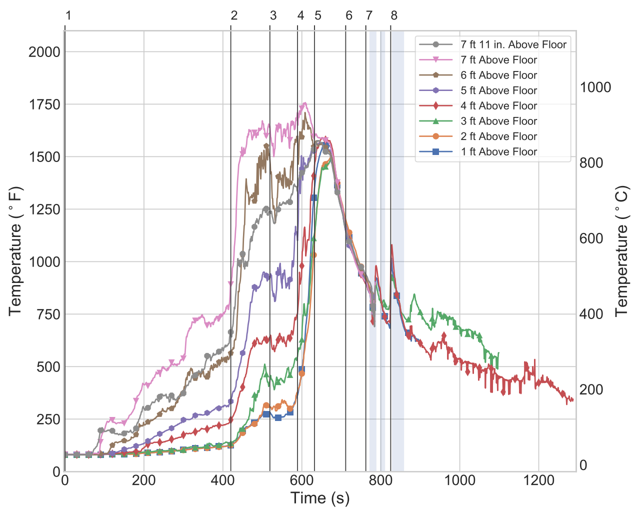
(b) After Firefighter Entry and Interior Suppression

Figure 3.114: Changes in flow during Experiment 3B. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

The time histories of the kitchen temperatures are presented in Figure 3.115. The temperature near the kitchen ceiling began to increase 70 s (1:10) post ignition. The fire grew, resulting in a temperature rise in the kitchen that ranged from 115 °F 1 ft above the floor to 870 °F 1 in. below the ceiling at the time of the living room ignition. Temperatures at all elevations in the kitchen increased at a faster rate as the living room fire grew in size. The kitchen window failed at 522 s (8:42), when kitchen temperatures ranged from 275 °F 1 ft above the floor to 1585 °F 1 ft below the ceiling.

After the kitchen window failed, temperatures in the kitchen remained relatively steady until the living room sliding glass door was vented at 589 s (9:49). The additional ventilation allowed the fire to transition to flashover as temperatures at all elevations exceeded 1100 °F, which occurred at 632 s (10:32) in the kitchen. At their peak, between 604 s (10:04) and 673 s (11:13), the kitchen temperatures ranged from 1490 °F to 1760 °F. After the kitchen transitioned to flashover, the temperature began to decrease as the oxygen in the compartment was consumed. The start of exterior water application at 768 s (12:48) further reduced temperatures to approximately 750 °F.

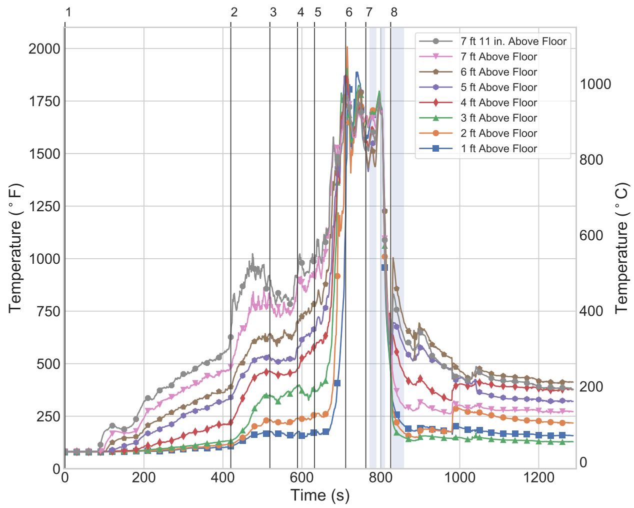
Temperatures briefly recovered between the two exterior water applications but had decreased to below 750 °F following the exterior water. At 825 s, several thermocouples showed an increase in temperature as a result of the apartment door being opened. It is important to note that by this point of the experiment, most of the thermocouples in the kitchen had already been compromised due to flow through the window, and it is unclear whether the remaining data were accurate from this point forward. However, the remaining data are still included to show the response to opening the door and the general decreasing trend following suppression.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

Figure 3.115: Kitchen temperatures for Experiment 3B. Blue shaded regions indicate time and duration of water flow.

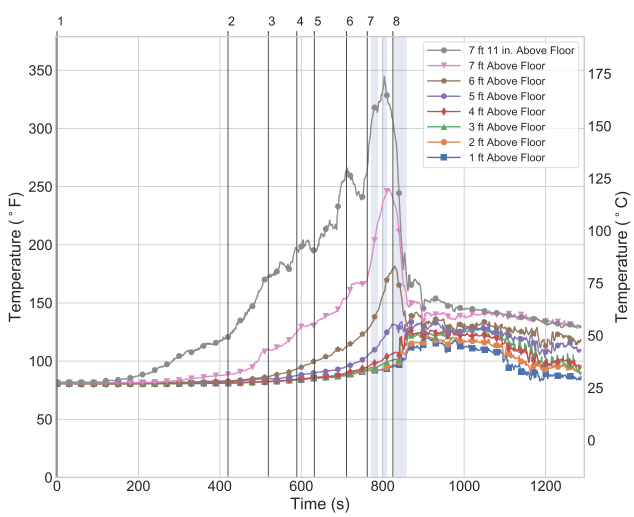
The time histories of the living room temperatures are presented in Figure 3.116. Temperatures near the living room ceiling began to increase 90 s post ignition. After ignition in the living room at 420 s (7:00), the temperatures began to increase at a faster rate. When the kitchen window failed at 522 s (8:42), a flow path was created from the living room sliding glass door to the kitchen window. The living room fire remained in a steady, ventilation-limited condition, with temperatures ranging between 150 °F 1 ft above the floor and 850 °F 1 in. below the ceiling. These conditions remained until the second half of the sliding glass door was vented, which provided a larger inlet. The additional oxygen increased the heat release rate of the fire, and the room transitioned to flashover at 714 s (11:54), 82 s after the kitchen transitioned to flashover. The living room remained in a post-flashover state with approximate temperatures of 1700 °F until firefighters initiated suppression. The living room temperatures dropped from about 1700 °F to under 750 °F in response to exterior water application through the sliding glass door, at 803 s (13:23). Opening the apartment door to begin interior suppression at 825 s (13:45) led to a brief increase of temperature, but the interior water flow reduced the living room temperatures, which continued decreasing toward ambient conditions thereafter.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

Figure 3.116: Living room temperatures for Experiment 3B. Blue shaded regions indicate time and duration of water flow.

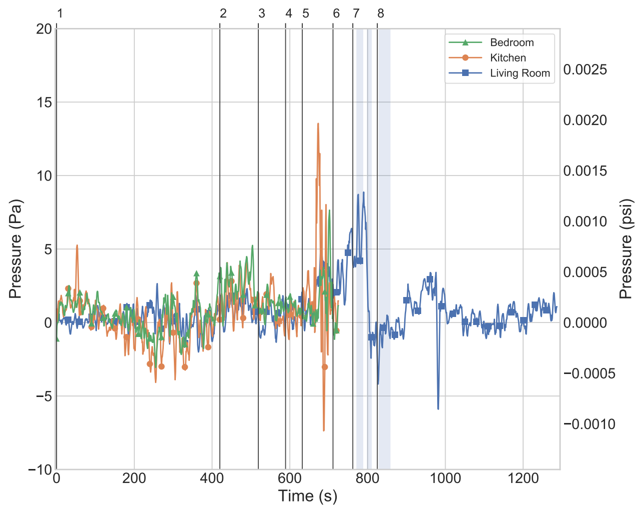
Temperatures in the bedroom of the fire apartment remained much lower than the kitchen and living room due to the closed bedroom door (see Figure 3.117). The temperatures near the ceiling began increasing at 120 s (2:00) as smoke leaked through the top of the bedroom door. Temperatures near the floor responded much later, at about 630 s (10:30). The temperatures peaked just as exterior fire control commenced, between 803 s (13:23) and 846 s (14:06), ranging between 105 °F 1 ft above the floor and 345 °F 1 in. below the ceiling. The start of interior suppression at 825 s (13:45) decreased temperatures.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

Figure 3.117: Bedroom temperatures for Experiment 3B. Blue shaded regions indicate time and duration of water flow.

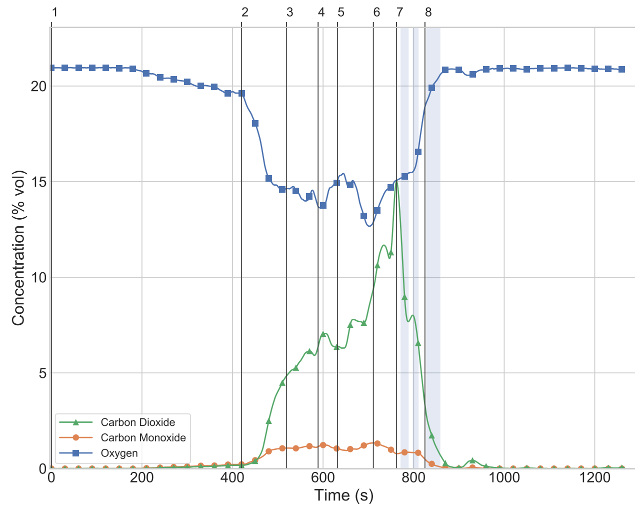
The time histories of the fire apartment pressures are presented in Figure 3.118. The open living room sliding glass door allowed combustion gases to flow from the fire room to the environment. This exhaust pathway limited the build-up of pressure in the fire apartment during the fire growth and fully developed stages. Therefore, the pressures in each room of the fire apartment remained near 0 Pa until the start of suppression. The living room pressure began increasing at 660 s (11:00) as the living room temperature increased and reached a peak of 9 Pa at 789 s (13:09). Water applied to living room from the exterior at 799 s (13:19) dropped the pressure as the gases cooled and contracted.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

Figure 3.118: Fire apartment pressures for Experiment 3B. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

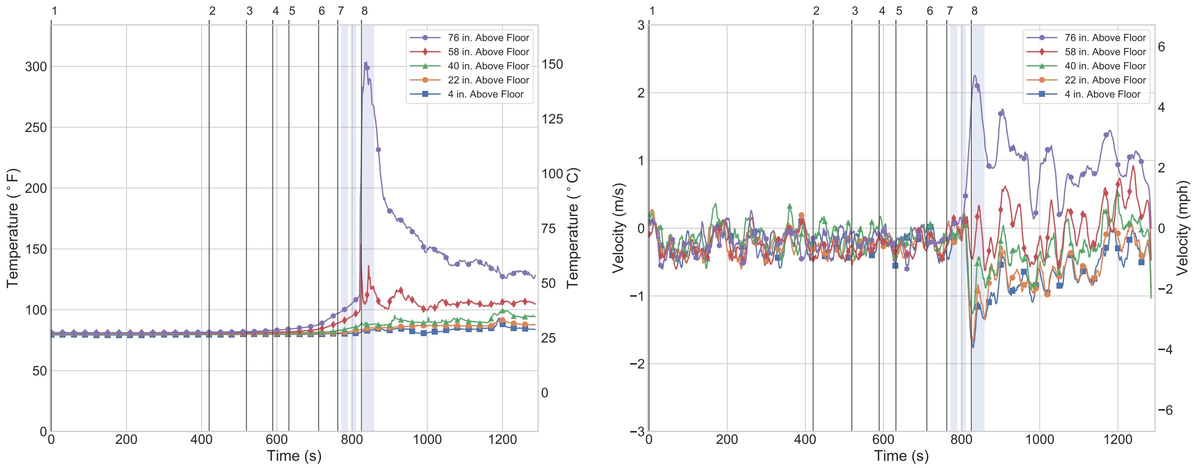
Gas concentrations in the living room of the fire apartment began to change at about 200 s (3:20) due to the fire growth in the kitchen (see Figure 3.119). The living room ignition at 420 s (7:00) increased the rate of change of the gas concentrations. The O_2 concentration fell below 15% at 487 s (8:07), which coincided with the pre-ventilation peak living room temperatures, because 15% is a typical threshold for sustaining combustion. At 600 s (10:00), the gas concentrations reached local peaks of 13.6% O_2, 1.3% (13,000 ppm) CO, and 7.1% CO_2. Venting the other half of the living room sliding glass door at 589 s (9:49) allowed additional fresh air into the living room. This led to an increase in the O_2 concentration and the living room transitioned to flashover about 60 s later. The peak gas concentrations occurred between 700 s (11:40) and 760 s (12:40), and were 12.7% O_2, 1.4% (14,000 ppm) CO, and 15.0% CO_2. Exterior fire control started at 768 s (12:48), which improved the gas concentrations. Ambient conditions returned by 960 s (16:00).



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

Figure 3.119: Living room gas concentrations for Experiment 3B. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened 825 s (13:45) post-ignition to allow for the suppression crew to enter the apartment. Figure 3.120 shows the temperatures and velocities recorded at the fire apartment door. Before the apartment door was opened, smoke leaking past the door increased the temperature at the top two sensors (58 in. and 76 in. above the floor) to over 100 °F. After the apartment door was opened, the temperature at the top sensor increased to 30 °F as gases exhausted out of the apartment at approximately 2 m/s (4 mph). At the 58 in. elevation, the flow was approximately 1 m/s (2 mph) fluctuating between inflow and outflow, and the temperature increased to 125 °F. Below the 58 in. elevation, flow was initially into the apartment at 1 m/s (2 mph) to 2 m/s (4 mph) as the vents in the fire room acted as the predominant exhaust for the higher pressure fire room gases. Following suppression, gas flow at all elevations slowed toward 0 m/s and temperatures decreased to ambient levels because the production of combustion gases had stopped.

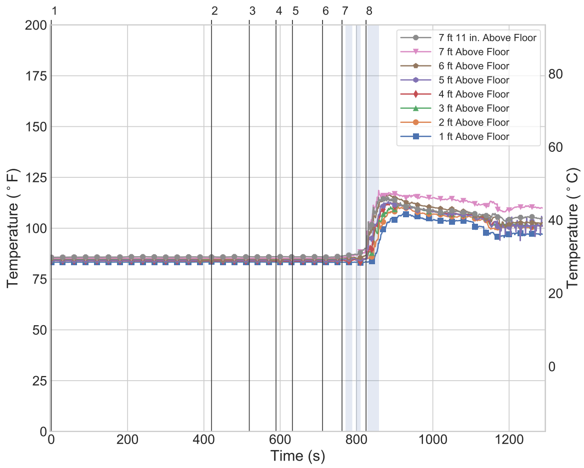


(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

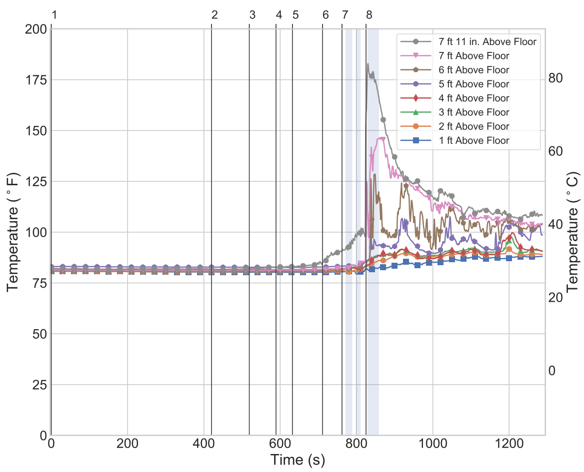
Figure 3.120: Temperatures and velocities at fire apartment (Apartment A) door for Experiment 3B. Blue shaded regions indicate time and duration of water flow.

Temperatures in the stairwell remained ambient and steady (about 85 °F) until 700 s (11:40) post ignition (see Figure 3.121). Smoke leaking through the top of the fire apartment door began to increase the temperature at 1 in. below the ceiling on the first floor. When the suppression crew opened the fire apartment door at 825 s (13:45), temperatures on the first and second floors increased in response to the smoke exhausting from the fire apartment into the stairwell. The response was greatest on the first floor, which reached peak temperatures ranging between 105 °F 5 ft above the floor and 185 °F 1 in. below the ceiling. Temperatures below 5 ft on the first floor did not increase above 90 °F. On the second floor, the peak temperatures ranged from 105 °F 1 ft above the floor to 120 °F 1 ft below the ceiling. The temperature on both floors then decreased toward ambient conditions. Temperature on the lower level did not show an increase throughout the experiment.

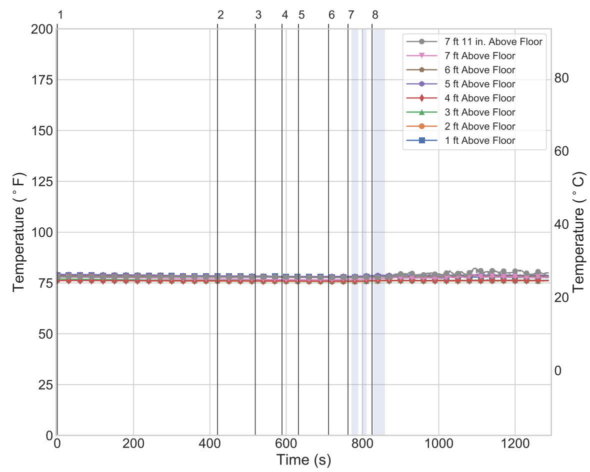


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825



(b) First-Floor Stairwell

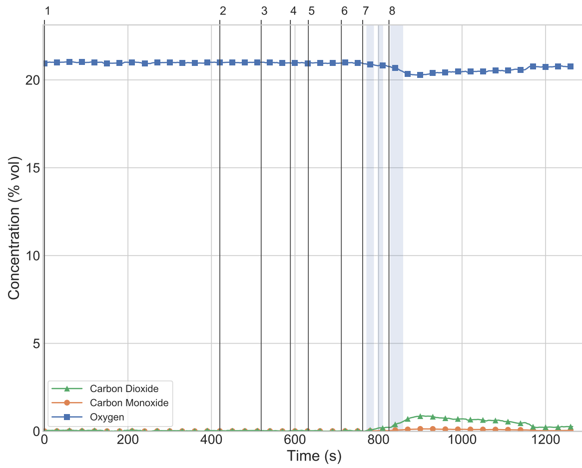


(c) Lower-Level Stairwell

Figure 3.121: Stairwell temperatures for Experiment 3B. Blue shaded regions indicate time and duration of water flow.

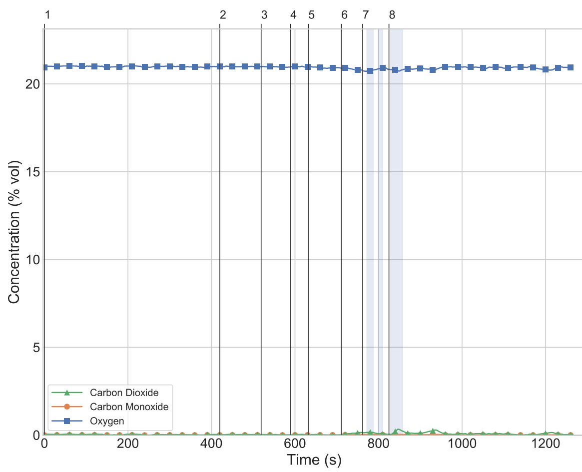
Stairwell pressures remained near ambient levels, between -2 Pa and 2 Pa for the duration of the experiment. The pressures did not respond noticeably to any fire changes or firefighter interventions.

Gas concentrations began to change on the second-floor of the stairwell after firefighters opened the fire apartment door at 1031 s (17:11), releasing smoke that filled the stairwell from the top down (see Figure 3.122). The O_2 concentration decreased to a minimum of 20.2% while CO_2 and CO concentrations increased to maximums of 0.9% and 0.2% (2000 ppm), respectively by 900 s (15:00). Gas concentrations remained near ambient on the lower level and first floor of the stairwell.

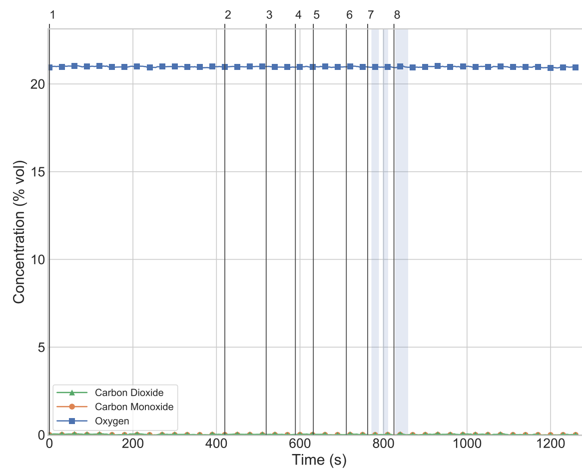


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825



(b) First-Floor Stairwell

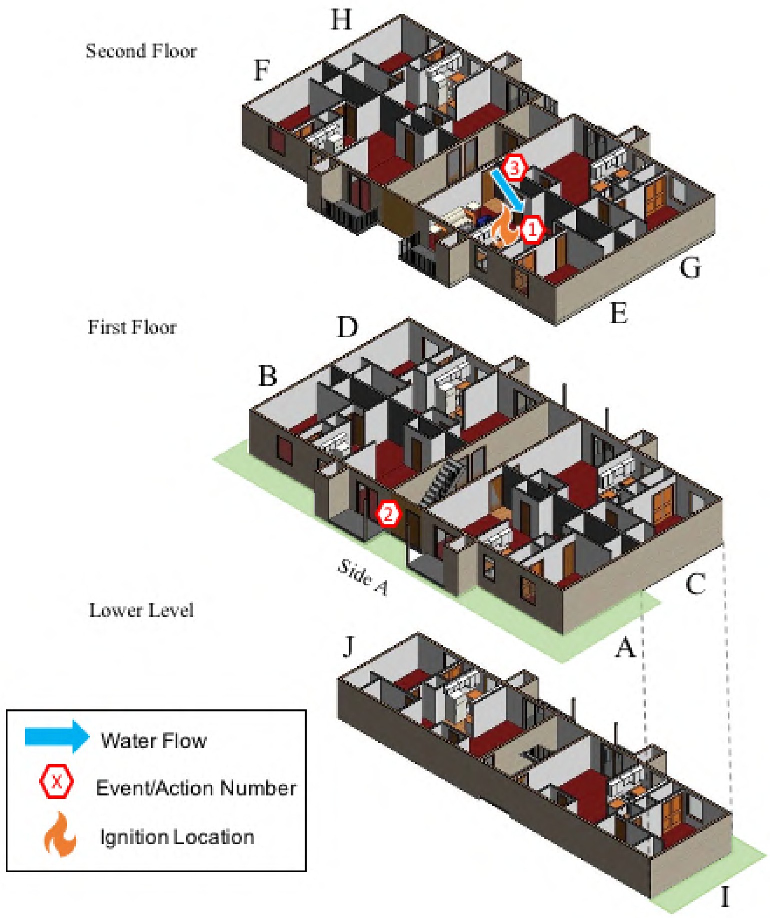


(c) Lower-Level Stairwell

Figure 3.122: Stairwell gas concentrations for Experiment 3B. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

3.10 Experiment 4A – Second-Floor Apartment Fire with Interior Suppression

Experiment 4A was conducted in Apartment E of 1980 Kimberly Village Lane, and it was designed to evaluate the use of interior suppression for a fire originating in the kitchen of a second-floor apartment. Prior to ignition, half of the living room sliding glass door was open and all other exterior windows and doors were closed, including the fire apartment door and doors to other apartments within the structure. During fire growth, the kitchen window failed, which led to combustion occurring at the window as the apartment became ventilation-limited. Firefighter intervention included entry to the structure, followed by entry into the fire apartment and flow-and-move suppression into the fire compartment. At necessary times throughout the experiment, water was applied from the exterior to the eaves on the front of the structure to limit exterior fire spread. Figure 3.123 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Open exterior door	13:00	780
3	Open apartment door; begin interior suppression	13:37	817

Figure 3.123: Time and sequence of actions and events for Experiment 4A.

The experimental volume included all areas of the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.124 shows the layout of the experimental volume with the instrument locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

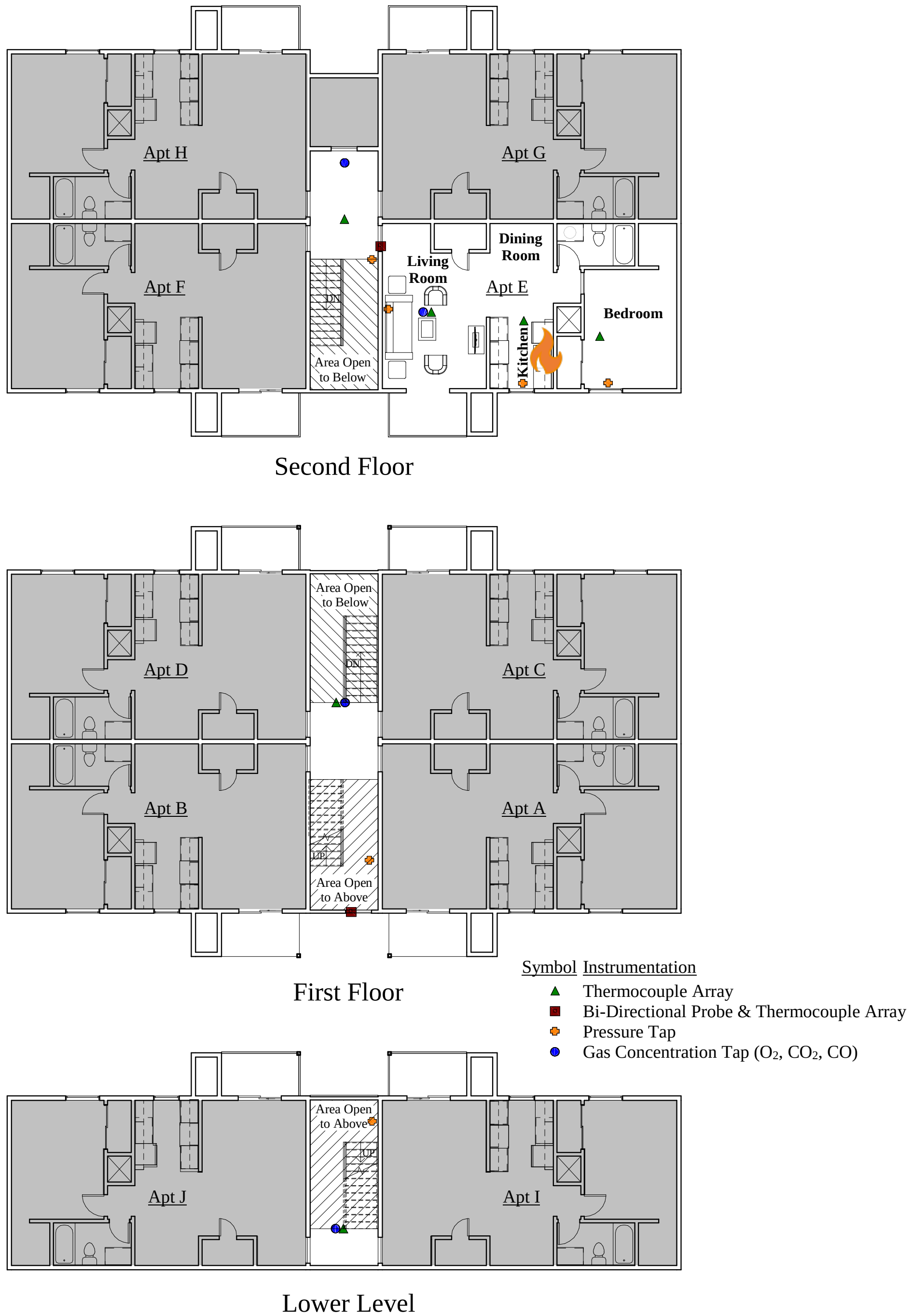


Figure 3.124: Instrumentation locations in Experiment 4A.

The kitchen and living room were furnished with the fuel loads described and photographed in Section 2.5. The bedroom was not furnished.

The fire in Experiment 4A was ignited via electric matches in two small, plastic waste containers; one was placed on the kitchen counter and the other on the floor next to the kitchen cabinets (t = 0 s). As the fire grew, a smoke layer developed throughout the apartment. The living room had a vaulted ceiling, 11 ft high at the peak, which provided additional volume for the smoke layer to fill. As the fire spread to the top of the kitchen cabinets, pieces of drywall began falling from the ceiling at 449 s (7:29). The ceiling drywall continued to fall in small pieces (less than approximately 1 ft^2) throughout the fire growth, which exposed the joists and attic space above the kitchen. At 464 s (7:44), the kitchen window started to fail in the form of a small crack at the top of the window which allowed smoke to exhaust to the exterior. Cracks continued to form in the window, increasing the size of the vent. However, the majority of the window remained intact until firefighter intervention. Figure 3.125 shows the condition of the kitchen window at 707 s (11:47), just over a minute before the suppression crew entered the structure for interior suppression. By that time, glass from the upper-left quarter and upper-right edge of the window had failed. Flames extended through the gaps in the window and ignited the eaves above.

Figure 3.125: An image showing the degree of damage to the kitchen window by 707 s (11:47) post ignition (73 s prior to firefighter intervention) in Experiment 4A.

The ceiling drywall continued to fall across the kitchen, causing the kitchen thermocouple tree to fall at 642 s (10:42). Large pieces of drywall (larger than 1 ft^2) fell at 701 s (11:41), and again at 824 s (13:44). The fire spread to the exposed joists above the kitchen and began to fill the open attic space with combustion gases. Figure 3.126 shows images of conditions in the kitchen and living room during the fire growth.

(a) Ceiling Drywall Began to Fall (449 s) (b) Fire Spread to Exposed Joists (716 s) (c) Suppression Crew Opened Apartment Door (817 s)

Figure 3.126: Images of conditions in the kitchen and living room during fire growth in Experiment 4A.

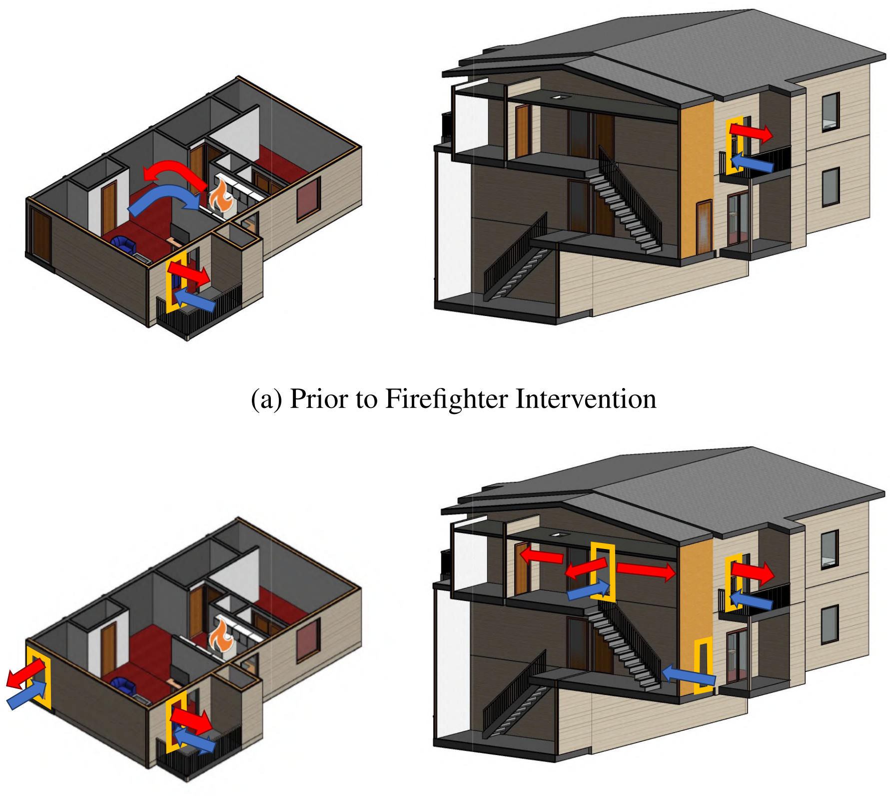
The first fire department intervention occurred at 780 s (13:00) post ignition with the opening of the exterior breezeway door. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded to the door of the fire apartment. At 817 s (13:37), the suppression crew opened the apartment door, began flowing water at 160 gpm from a 7/8 in. smooth bore nozzle operated in an O pattern attached to 200 ft of 1 3/4 in. hoseline, and advanced into the apartment. Figures 3.127a and 3.127b depict the layer height observed at entry due from the failed kitchen ceiling. Note: the failed ceiling allowed combustion products produced from the kitchen fire to flow into the attic space. When combined with the vaulted living room ceiling and vented kitchen window, these factors limited the smoke layer development in the apartment. The open kitchen window allowed flames to extended to the exterior of the structure and into the eaves. Flames impinged upon the eave-line for approximately 157 s before exterior water was used to extinguish fire in the eaves; however, flames had already spread into the attic. Overhaul of the second-floor fire and exposure apartments were needed to gain access to the attic space for final suppression. The hoseline was open for a total of 76 s and flowed 184 gallons of water during the initial interior suppression operation. Water flow after 895 s (14:55) was utilized during overhaul operations.

(a) From Stairwell (b) From Doorway

Figure 3.127: Apartment conditions during time of entry from the stairwell during Experiment 4A.

The flow of combustion gases and fresh air during Experiment 4A are sketched in Figure 3.128.

As the fire grew in the kitchen, high-temperature, lower density fire gases rose and began to fill the fire compartment from the top down. The kitchen was open to the living room. As a result, the smoke layer took longer to descend to the floor because of the peaked ceiling. Once the hot gas layer reached the top of the open sliding glass door in the living room, gases began exhausting to the outdoor environment. At the same time, entrainment from the fire plume caused air to be drawn through the bottom of the sliding glass door into the apartment (see Figure 3.128a). Firefighters then entered through the exterior breezeway and fire apartment doors to begin interior suppression. Because the fire apartment was on the second floor, there was minimal thermal or smoke exposure impact to the lower level and first floor. Combustion gases flowed into the enclosed stairwell through the top of the fire apartment door as cooler, ambient air was entrained at the bottom (see Figure 3.128b). Firefighters knocked down the fire, which stopped the production of combustion gases.

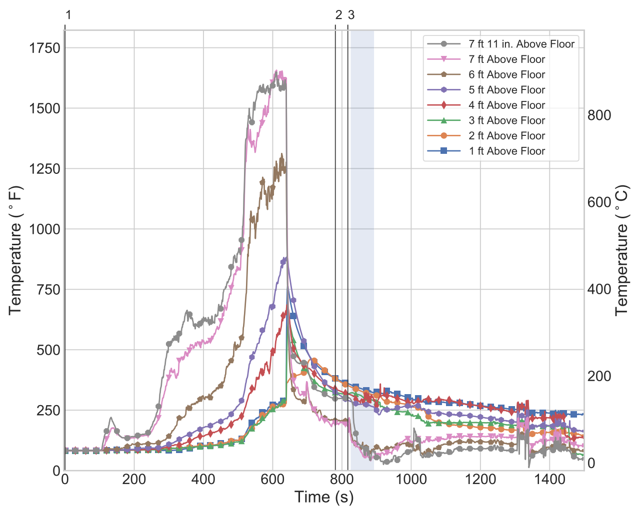


(a) Prior to Firefighter Intervention

(b) After Opening the Fire Apartment Door

Figure 3.128: Changes in flow during Experiment 4A. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

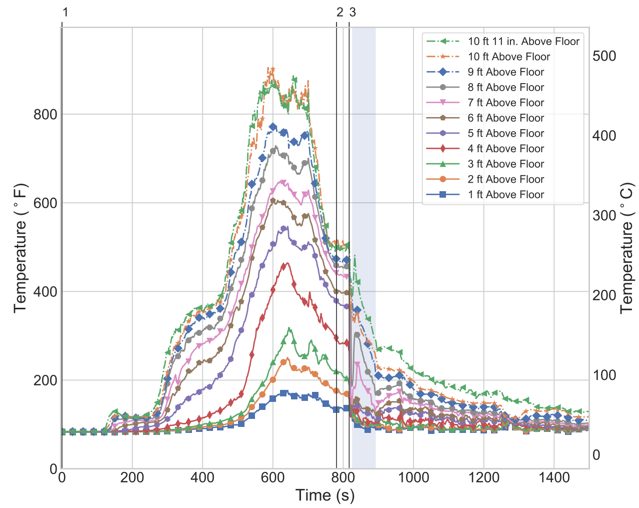
The time histories of the kitchen temperatures are presented in Figure 3.129. The temperature near the kitchen ceiling began to increase 110 s (1:50) post ignition. After 450 s (7:30), temperatures near the ceiling increased faster as fire spread up the cabinets. Temperatures near the floor increased more slowly due to the buoyant nature of combustion gases and the cool air entrained near the floor from the half open living room sliding glass door. At 642 s (10:42), the thermocouple array fell due to damage to the ceiling drywall as shown by the sharp drop in temperature in Figure 3.129. Prior to the sensors falling, the kitchen temperatures ranged from 295 °F 1 ft above the floor to 1605 °F 1 in. below the ceiling. For the remainder of the experiments, the kitchen temperatures reported values consistent with thermocouples on the ground, likely under debris.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817

Figure 3.129: Kitchen temperatures for Experiment 4A. Blue shaded regions indicate time and duration of water flow.

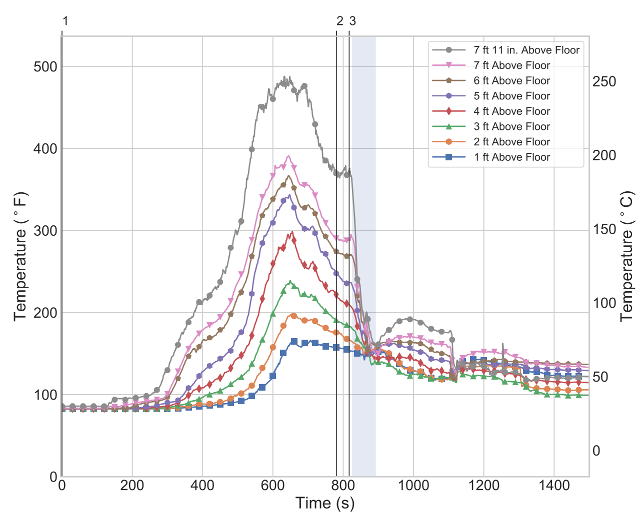
During the growth stage of the fire, temperatures in the living room behaved similarly to those in the kitchen, but at lower magnitudes (see Figure 3.130). The temperature near the living room ceiling began to increase 120 s (2:00) post ignition. The temperatures became stratified as temperatures near the ceiling increased due to the smoke layer filling the volume of the vaulted ceiling. Temperatures near the floor increased more slowly due to the cool air entrained from the open living room sliding glass door. At their peak, between 586 s (9:46) and 643 s (10:43), the living room temperatures ranged from 180 °F 1 ft above the floor to 905 °F 1 ft below the ceiling. Temperatures in the living room then began to steadily decrease prior to any additional ventilation, an indication the compartment became ventilation-limited. When the suppression crew opened the apartment door at 817 s (13:37), temperatures in the living room ranged between 135 °F 1 ft above the floor to 515 °F 1 ft below the ceiling. Temperatures at all elevations decreased in response to suppression, and continued to decrease toward ambient conditions thereafter. The temporary drop in all measured values at the start of suppression is likely a result of water hitting the sensors. The values recovered after the water evaporated and continued to steadily decline.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817

Figure 3.130: Living room temperatures for Experiment 4A. Blue shaded regions indicate time and duration of water flow.

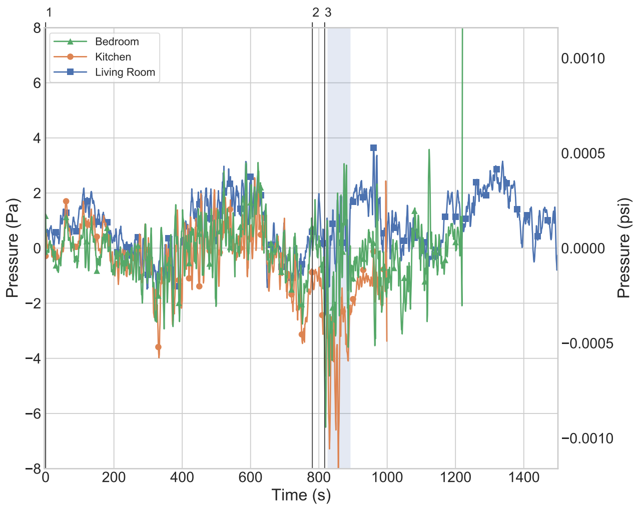
Temperatures in the bedroom of the fire apartment behaved similarly to those in the living room (see Figure 3.131). Temperatures near the ceiling began to increase 130 s (2:10) post ignition. Near the floor, temperatures did not begin increasing until 500 s (8:20). At their peak, between 630 s (10:30) and 660 s (11:00), temperatures in the bedroom ranged from 165 °F 1 ft above the floor to 490 °F 1 in. below the ceiling. Similar to the living room, the bedroom temperatures then began to steadily decrease, an indication the fire became ventilation-limited. When the suppression crew opened the apartment door at 817 s (13:37), temperatures in the bedroom ranged between 155 °F 1 ft above the floor to 375 °F 1 in. below the ceiling. Bedroom temperatures quickly decreased upon the start of suppression.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817

Figure 3.131: Bedroom temperatures for Experiment 4A. Blue shaded regions indicate time and duration of water flow.

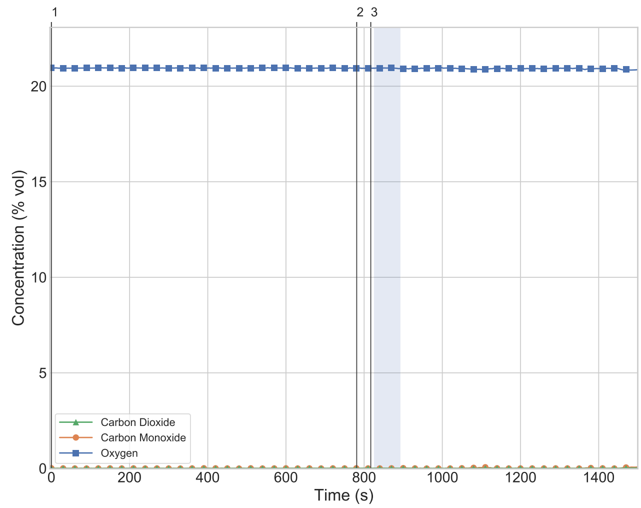
The time histories of the fire apartment pressures are presented in Figure 3.132. The open sliding glass door in the living room allowed combustion gases to flow to the lower pressure exterior which limited pressure build-up in the apartment. As a result, the pressures in each room of the fire apartment remained near ambient conditions. At the start of suppression, however, the cooling of gases led to gas contraction and apartment pressures to reach negative peaks of -8 Pa in the kitchen, -7 Pa in the bedroom, and -2 Pa in the living room. The pressures then steadily returned to ambient conditions following suppression.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817

Figure 3.132: Fire apartment pressures for Experiment 4A. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

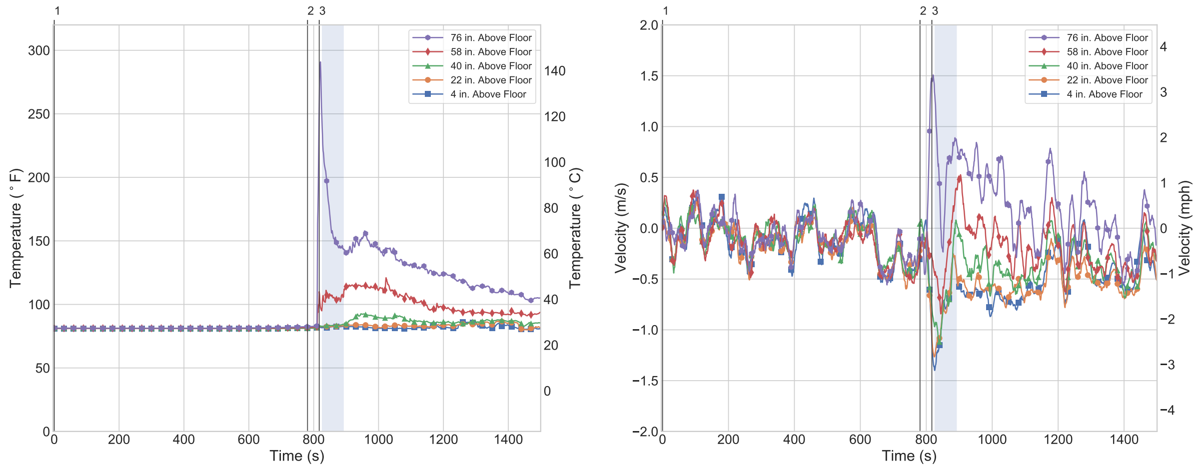
Gas concentrations in the living room of the fire apartment reflected ambient conditions throughout the duration of the experiment (see Figure 3.133). The smoke layer did not descend low enough to affect the gas sampling port installed 4 ft above the floor due to the additional volume of the vaulted living room ceiling that filled first. Additionally, the failed ceiling in the kitchen allowed fire gases to exhaust into the attic space above, limiting further layer descent in the fire apartment.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817

Figure 3.133: Living room gas concentrations for Experiment 4A. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened 817 s (13:37) post-ignition to allow for the suppression crew to the enter the apartment. Figure 3.134 shows the temperatures and velocities recorded at the fire apartment door. After the apartment door was opened, the temperature at the top sensor increased to 290 °F and flowed out of the apartment at approximately 1.5 m/s (3 mph). At the 58 in. elevation and below, flow was initially into the apartment at 1 m/s (2 mph) as the vents in the fire room acted as the predominant exhaust vent for the higher pressure fire room gases. The thermocouple at the 58 in. elevation did measure an increase in temperature as the flow fluctuated between inflow and outflow. Following suppression, gas flow out the door slowed toward 0 m/s because the production of combustion gases had stopped.



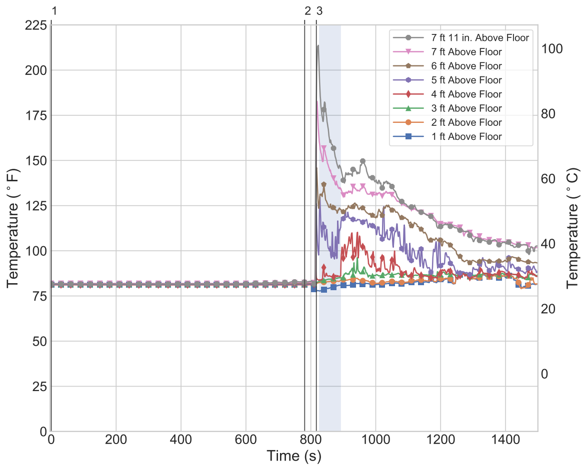
(a) Temperature

(b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817

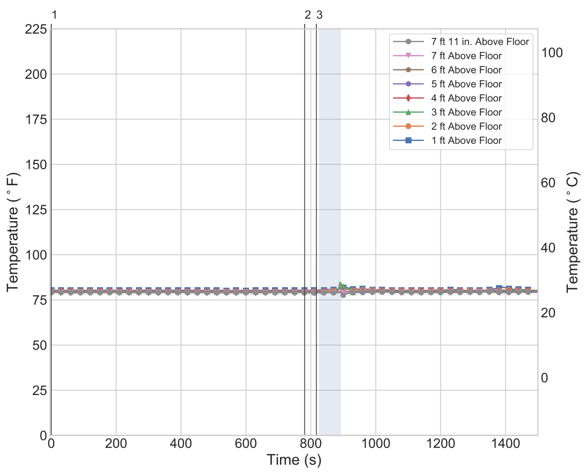
Figure 3.134: Temperatures and velocities at fire apartment (Apartment E) door for Experiment 4A. Blue shaded regions indicate time and duration of water flow.

Temperatures in the stairwell remained ambient and steady (about 80 °F) until firefighters opened the fire apartment door (see Figure 3.135). Temperatures near the ceiling on the second-floor spiked in response to the smoke exhausting from the fire apartment into the stairwell. Measurements from 4 ft above the floor to 1 in. below the ceiling reached peak temperatures between 110 °F and 215 °F, then steadily returned to ambient conditions due to suppression and ventilation. Temperatures below 4 ft on the second-floor did not have a noticeable increase. Likewise, the temperature on the first floor and lower level did not experience an increase in temperatures throughout the experiment.

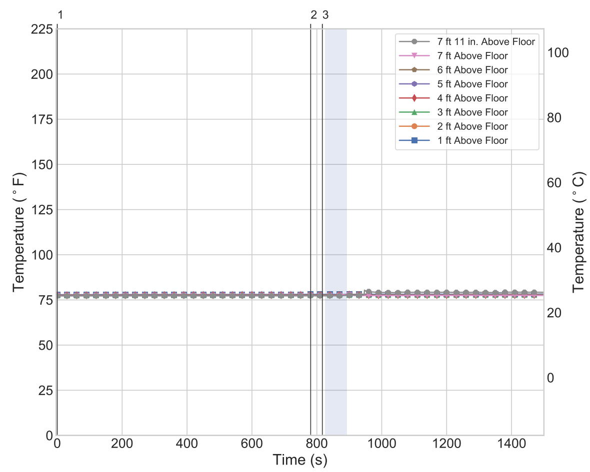


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817



(b) First-Floor Stairwell

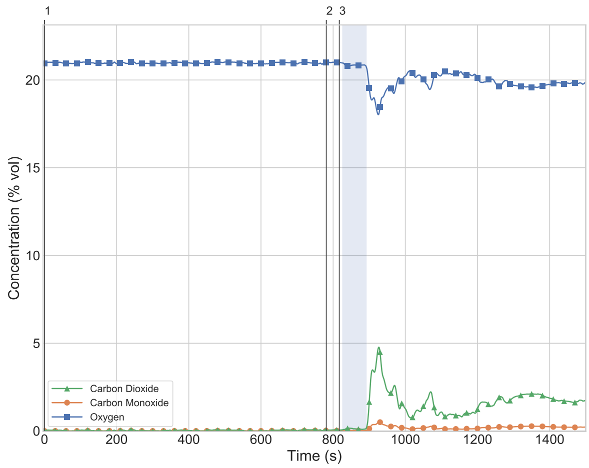


(c) Lower-Level Stairwell

Figure 3.135: Stairwell temperatures for Experiment 4A. Blue shaded regions indicate time and duration of water flow.

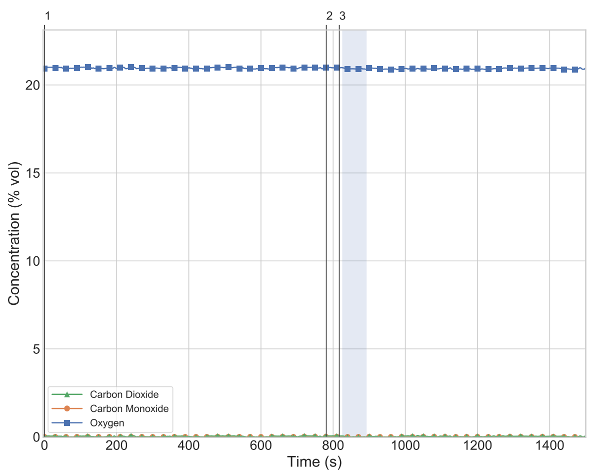
Pressures in the stairwell remained near ambient conditions, between ± 2 Pa, for the duration of the experiment. The pressures did not respond noticeably to any fire changes or firefighter interventions.

Gas concentrations began to change on the second floor of the stairwell after firefighters opened the fire apartment door at 817 s (13:37), smoke flowed from the apartment into the stairwell, filling it from thetop down (see Figure 3.136). The smoke layer remained above the 4 ft measurement location during interior suppression operations. Gas continued to flow into the stairwell following suppression (see Figure 3.134) and the smoke layer then descended to the measurement location (4 ft above the floor). The O_2 concentration decreased to a minimum of 18.0% while CO_2 and CO concentrations increased to maximums of 4.8% and 0.5% (5000 ppm) by 925 s (15:25). Gas concentrations remained near ambient on the lower level and first floor of the stairwell.

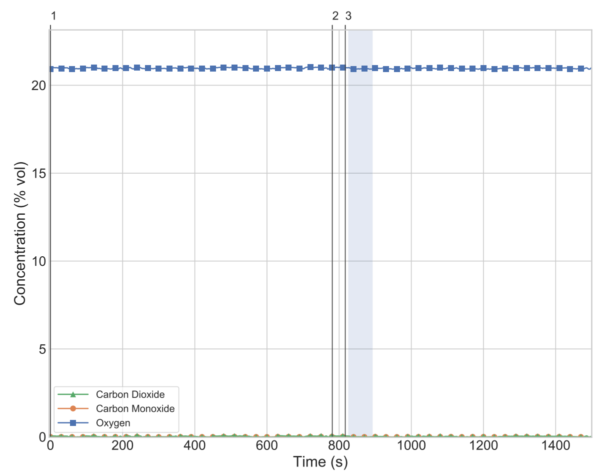


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	780
3	Open apartment door; begin interior suppression	817



(b) First-Floor Stairwell

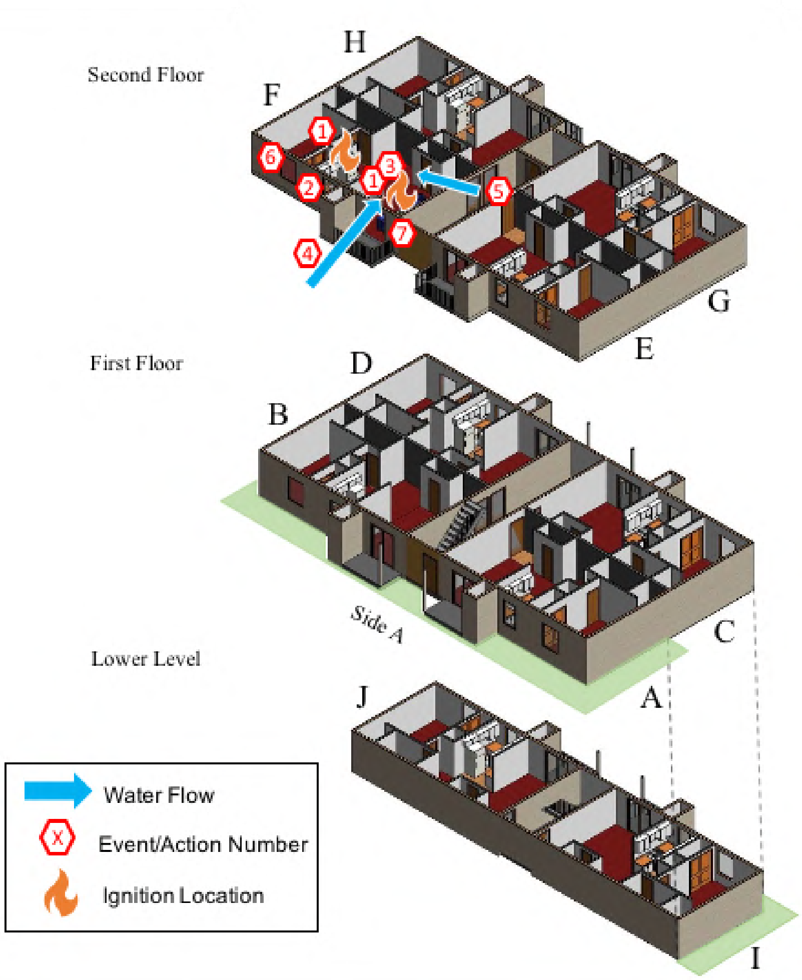


(c) Lower-Level Stairwell

Figure 3.136: Stairwell gas concentrations for Experiment 4A. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

3.11 Experiment 4B – Second-Floor Apartment Fire with Exterior Fire Control

Experiment 4B was conducted in Apartment F of 1980 Kimberly Village Lane, and it was designed to evaluate the use of exterior fire control for a fire that originated in the kitchen and living room of a second-floor apartment. Prior to ignition, half of the living room sliding glass door was open, the bedroom door was closed, and all other exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The fire was allowed to grow until it reached steady-state in the living room and kitchen before any firefighter intervention occurred. Firefighter intervention included venting the kitchen window, exterior fire control and a transition into the apartment for follow-up interior suppression. Hydraulic ventilation was used after suppression to remove smoke from the structure. Figure 3.137 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignitions in kitchen and living room	00:00	0
2	Vent kitchen window	07:31	451
3	Flashover in living room	08:50	530
4	Exterior fire control	09:01	541
5	Open apartment door; begin interior suppression	09:46	586
6	Open bedroom window	12:43	763
7	Hydraulic ventilation for 106 s	14:27	867

Figure 3.137: Time and sequence of actions and events for Experiment 4B.

The experimental volume included all areas of the fire apartment as well as the enclosed stairwell. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.138 shows the layout of the experimental volume with the instrument locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

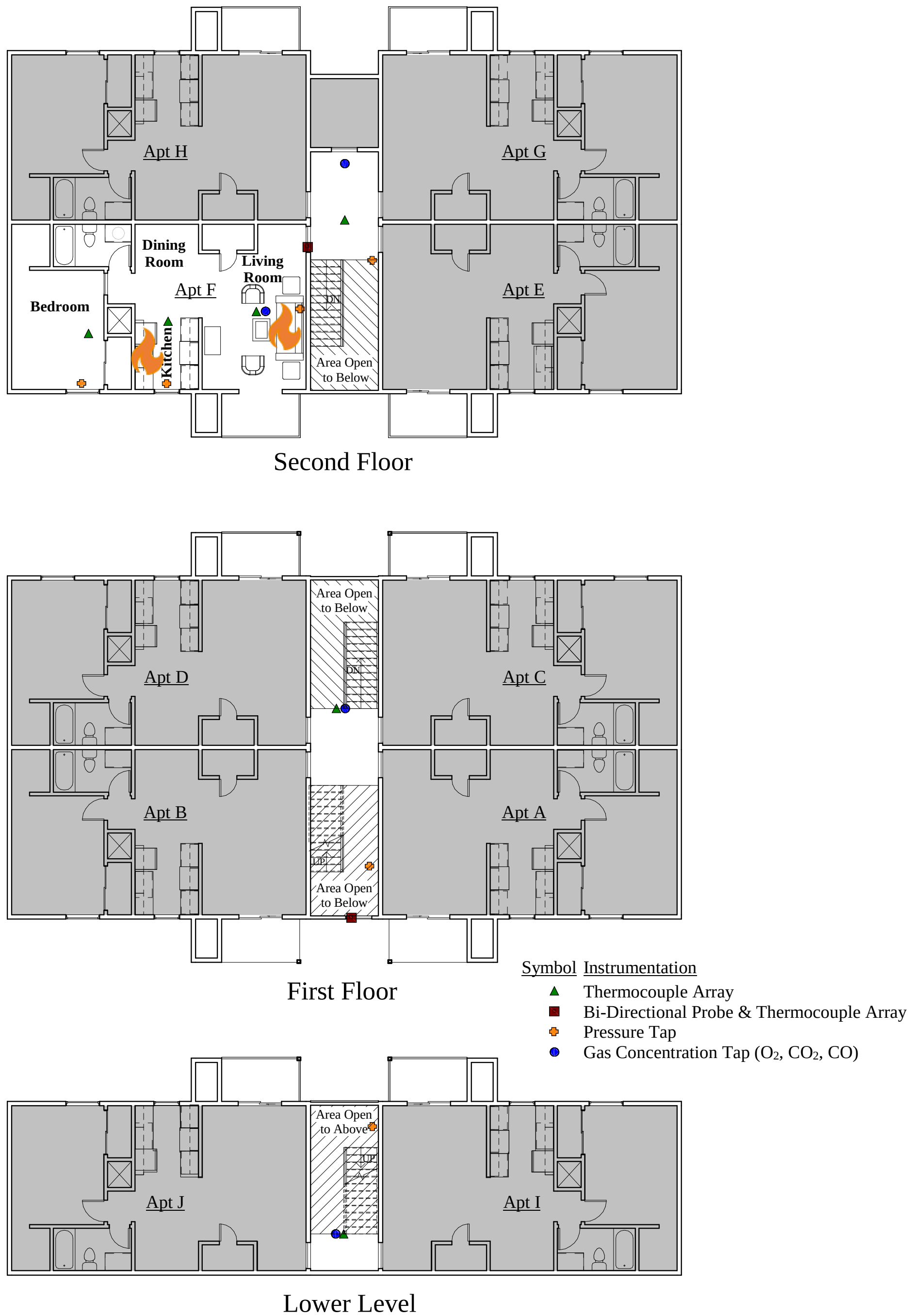


Figure 3.138: Instrumentation locations in Experiment 4B.

The kitchen and living room were furnished with the fuel loads described and photographed in Section 2.5.

The fire in Experiment 4B was ignited by electric matches in the kitchen and the living room (t = 0 s) simultaneously. Ignition in the kitchen was in a small, plastic waste container on the counter, while ignition in the living room was next to the arm of the sofa, furthest from the sliding glass door. A smoke layer formed throughout the fire apartment and began showing out of the open living room sliding glass door at 142 s (2:22). The smoke layer had descended to the floor by 295 s (4:55).

The first firefighter intervention was breaking the kitchen window at 451 s (7:31) to provide horizontal ventilation to the apartment (see Figure 3.139a). Within 30 s, flames began to extend out of the open living room sliding glass door. At 530 s (8:50), the living room reached flashover. The suppression crew began exterior fire control at 541 s (9:01) by applying water from the front of the structure flowing 160 gpm from a 7/8 in. smooth bore nozzle attached to 200 ft of 1 3/4 in. hoseline (see Figure 3.139b). The nozzle firefighter swept the eave above the living room sliding glass door for 8 s, then directed the hose stream at the sliding glass door lintel for another 8 s to disperse water in the living room. The total time for exterior water application was 16 s, resulting in 45 gallons of water flowed. There was no fire showing after exterior water application. Figure 3.139 shows images of conditions on the side A exterior during different stages of firefighter intervention.

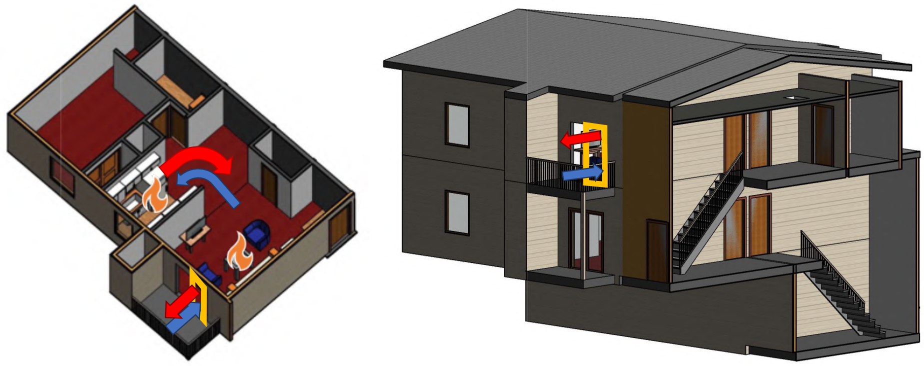
(a) Immediately after Venting the Kitchen Window (451 s)

(b) The Start of Exterior Water Application (541 s)

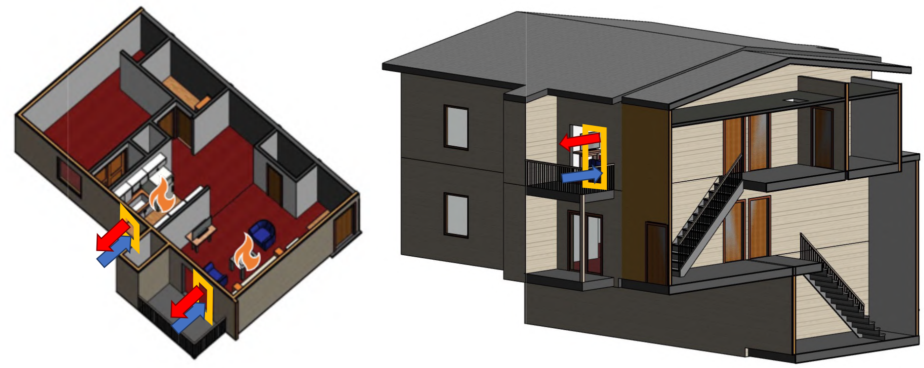
Figure 3.139: Images of conditions on the side A exterior during firefighter interventions in Experiment 4B.

The suppression crew then opened the exterior breezeway door and proceeded to the fire apartment door. The fire apartment door was opened at 586 s (9:46), and the suppression crew immediately began flowing water and advanced into the apartment. The initial interior suppression operation lasted 42 s and flowed 95 gallons of water. Any water flow after the initial interior suppression operation ended at 628 s (10:28) was utilized during overhaul operations. The bedroom window was opened at 763 s (12:43) to provide additional ventilation in the fire apartment. At 867 s (14:27), the suppression crew began hydraulic ventilation out of the living room sliding glass door using a solid stream in an O pattern. Hydraulic ventilation continued until 973 s (16:13), for a total of 106 s (1:46) and 272 gallons of water.

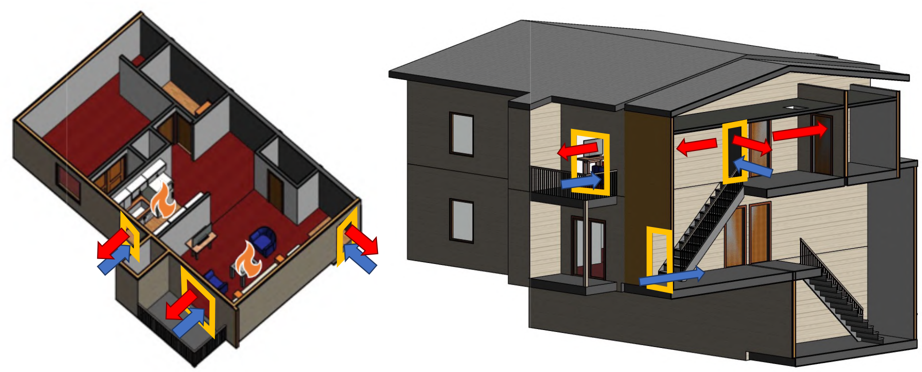
The flow of combustion gases and fresh air during the experiment are sketched in Figures 3.140–3.141. As the fire grew in the kitchen and living room, high-temperature, lower density fire gases rose and began to fill the fire compartment from the top down. Once the hot gas layer reached the top of the half open sliding glass door in the living room, gases began exhausting to the environment. Entrainment from the fire plume caused air to be drawn through the bottom of the sliding glass door into the fire apartment (see Figure 3.140a). The kitchen window was subsequently vented, which provided a new exhaust for the higher pressure gases. The gases exhausted out of the top portion of the window while cooler, ambient air was entrained through the lower portion (see Figure 3.140b). Firefighters began exterior fire control 90 s later, followed by entry through the exterior breezeway and fire apartment doors to conduct interior suppression. Combustion gases flowed into the low-pressure enclosed stairwell through the top of the fire apartment door as cooler, ambient air was entrained at the bottom (see Figure 3.140c).



(a) Prior to Firefighter Intervention



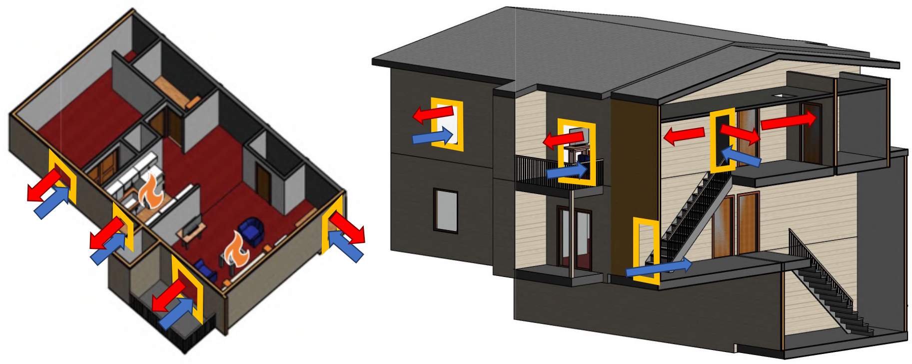
(b) After the Kitchen Window Was Vented



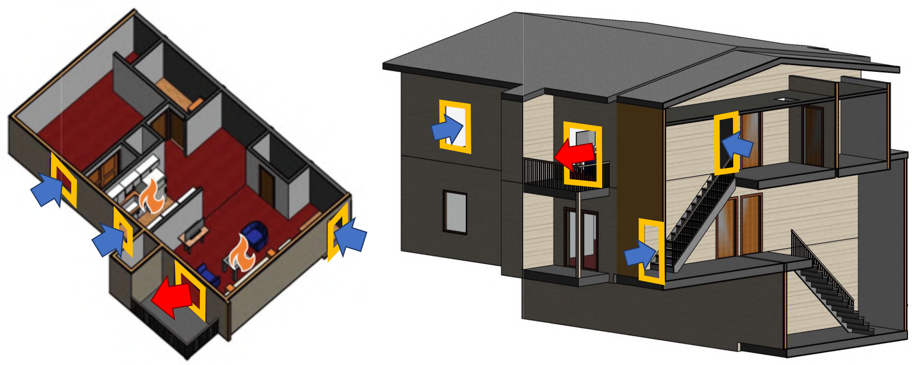
(c) After Firefighter Entry and Interior Suppression

Figure 3.140: Changes in flow during Experiment 4B pre-knock down. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

Firefighters knocked down the fire, which stopped the production of gases and allowed the structure to naturally ventilate. The bedroom window was then opened to increase ventilation (see Figure 3.141a). About 5 min. after suppression, firefighters began hydraulic ventilation out of the sliding glass door. This exhausted gases out of the fire compartment while entraining fresh air through the structure from both the exterior breezeway door and the open bedroom window (see Figure 3.141b).



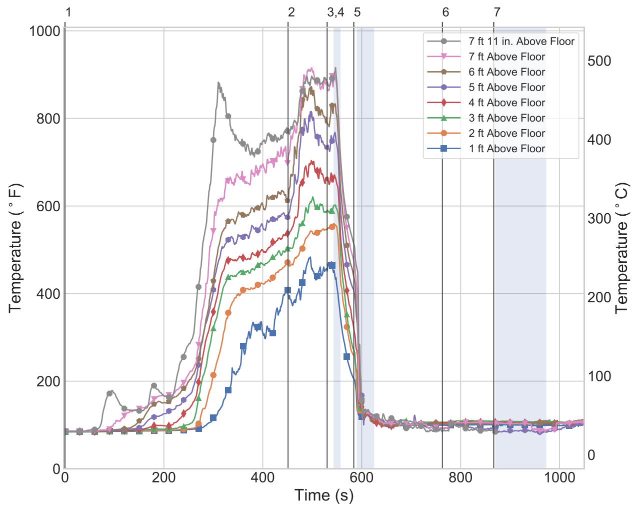
(a) After Opening the Bedroom Window



(b) After Starting Hydraulic Ventilation

Figure 3.141: Changes in flow during Experiment 4B post-knock down. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings present during this experiment.

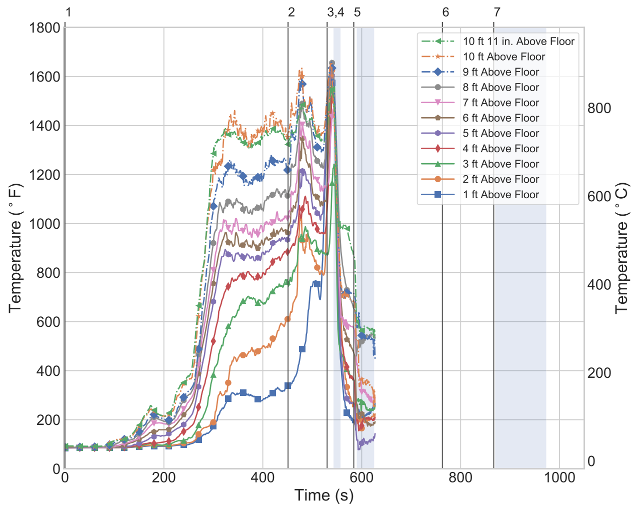
The time histories of the kitchen temperatures are presented in Figure 3.142. The temperature near the kitchen ceiling began to increase 70 s (1:10) post ignition. The kitchen temperatures increased rapidly between 260 s (4:20) and 310 s (5:10) as fire spread within the kitchen, but growth slowed as the fire consumed the oxygen available for combustion. Prior to ventilation of the kitchen windows, temperatures ranged from 400 °F 1 ft above the floor to 800 °F 1 in. below the ceiling. Bi-directional flow was established at the kitchen window after it was opened. The inlet supplied additional oxygen to the kitchen fire, which led to a temperature rise as the heat release of the fire increased. The kitchen temperatures reached peaks at 495 s (8:15) between 485 °F 1 ft above the floor and 920 °F 1 ft below the ceiling. The temperatures remained elevated until the start of suppression at 541 s (9:01). The exterior water application reduced the kitchen temperatures to between 210 °F 1 ft above the floor and 525 °F 1 in. below the ceiling. The interior suppression at 586 s (9:46) further reduced temperatures at all elevations to below 150 °F. The kitchen temperatures continued decreasing toward ambient conditions for the remainder of the experiment.



	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

Figure 3.142: Kitchen temperatures for Experiment 4B. Blue shaded regions indicate time and duration of water flow.

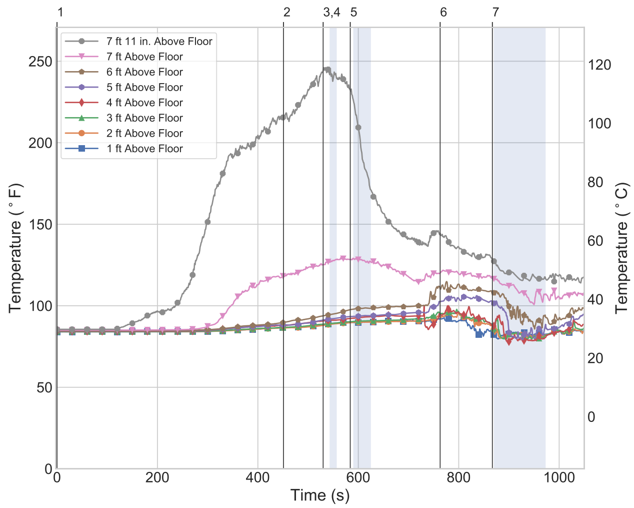
Temperatures in the living room behaved similarly to those in the kitchen, but at higher temperatures (see Figure 3.143). Similar to the kitchen temperatures, the living room temperature increased rapidly between 260 s (4:20) and 310 s (5:10), then reached a steady, ventilation-limited state. The temperatures ranged from 215 °F 1 ft above the floor to 1455 °F 1 ft below the ceiling. Prior to the kitchen window vent being established, the only exhaust path was through the living room sliding glass door. Venting the kitchen window at 451 s (7:31) led to a more efficient transfer of gases through the apartment. The additional vent led to increased intake (i.e., additional oxygen) through the living room sliding glass door, which led to an increase in heat release rate. The living room temperatures began increasing, and within 80 s, the living room transitioned to flashover as temperatures at all elevations exceeded 1100 °F. The peak temperatures which occurred immediately prior to the start of suppression, ranged from 1245 °F to 1665 °F. The exterior water application began at 541 s (9:01), 11 s after the living room transitioned through flashover. The suppression immediately reduced the living room temperatures. At the time of interior suppression, temperatures had all dropped below 600 °F. The living room thermocouples were damaged during suppression, so data after 628 s (10:28) are omitted from Figure 3.116.



	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

Figure 3.143: Living room temperatures for Experiment 4B. Data after 555 s (9:15) is omitted because the thermocouple signals became irregular due to damage during suppression. Blue shaded regions indicate time and duration of water flow.

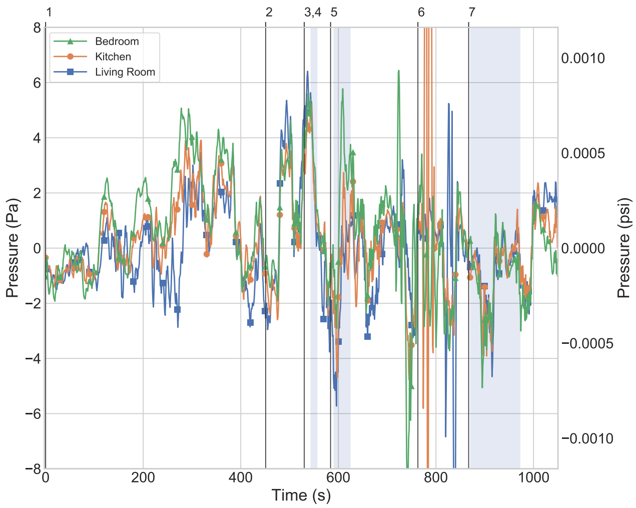
Temperatures in the bedroom of the fire apartment remained much lower than the kitchen and living room due to the closed bedroom door (see Figure 3.144). Temperatures near the ceiling began to increase 115 s (1:55) post ignition due to smoke leaking past the closed door. Temperatures at 6 ft and below increased slowly, but did not exceed 115 °F throughout the entire experiment. The temperatures at 1 in. and 1 ft below the ceiling reached peaks 245 °F and 130 °F, respectively. The peak temperatures corresponded with the living room transition to flashover, at 530 s (8:50). The temperatures near the ceiling decreased in response to the start of suppression and the ventilation of the bedroom window and continued to decrease thereafter. The start of hydraulic ventilation at 867 s (14:27) slightly increased the rate at which the bedroom temperatures returned to ambient conditions.



	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

Figure 3.144: Bedroom temperatures for Experiment 4B. Blue shaded regions indicate time and duration of water flow.

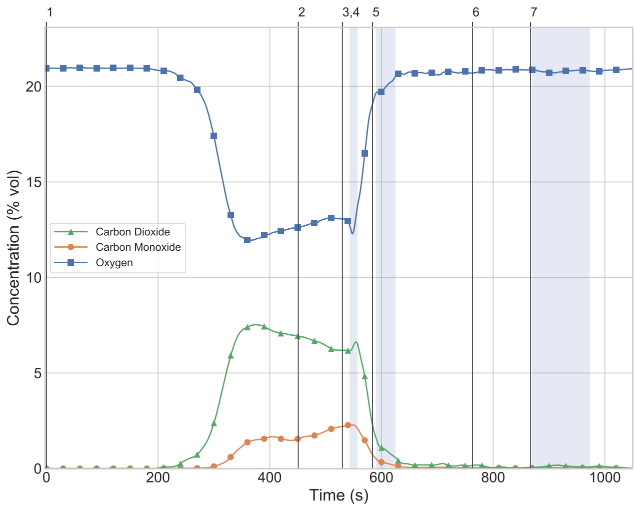
The time histories of the fire apartment pressures are presented in Figure 3.145. The fire apartment pressures increased during the fire growth stage as the fire generated more pressure than could be relieved by the open living room sliding glass door. The pressures reached peaks of 5 Pa in the bedroom, 4 Pa in the kitchen, and 3 Pa in the living room. At 382 s (6:22), the fire apartment pressures quickly dropped to negative values, an indication the fire had become ventilation-limited. The pressures remained between -1 Pa and -3 Pa until the kitchen window was vented, allowing fire growth that increased the pressure in the apartment. The fire apartment pressures peaked at 6 Pa when the living room transitioned to flashover at 530 s (8:50). The start of suppression 11 s later, however, caused the apartment pressures to become negative due to the cooling and contraction of the gases. The pressures reached minimums of -3 Pa in the bedroom, -5 Pa in the kitchen, and -6 Pa in the living room. After suppression ended, the apartment pressures returned to approximately ambient conditions as gases in the apartment equalized with the outside via the open vents. The pressure taps were impacted during overhaul, resulting in spikes between 720 s (12:00) and 840 s (14:00). The apartment pressures became negative during hydraulic ventilation, reaching peaks of -4 Pa to -5 Pa.



	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

Figure 3.145: Fire apartment pressures for Experiment 4B. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

Gas concentrations in the living room of the fire apartment began to change at about 200 s (3:20) due to the fire growth in the apartment (see Figure 3.146). The O_2 concentration fell below 15% at 316 s (5:16). This time coincided with temperatures in the kitchen and living room reaching steady values, a confirmation the fire had become ventilation-limited. At 365 s (6:05), the gas concentrations reached local peaks of 11.9% O_2, 1.5% (15,000 ppm) CO, and 7.5% CO_2. The O_2 and CO concentrations continued to improve due to an increase in structure ventilation until the start of exterior fire control, which mixed the gases in the apartment and temporarily impacted the gas concentration measurements. At the start of exterior fire control, the gas concentrations had reached peaks of 12.3% O_2, 2.3% (23,000 ppm) CO, and 6.6% CO_2. The gas concentrations then rapidly improved as the fire was suppressed, reaching 19% O_2, 0.5% (5,000 ppm) CO, and 1.8% CO_2 before the start of interior suppression. Interior suppression further improved gas concentrations, which reached ambient conditions by 800 s (13:20).

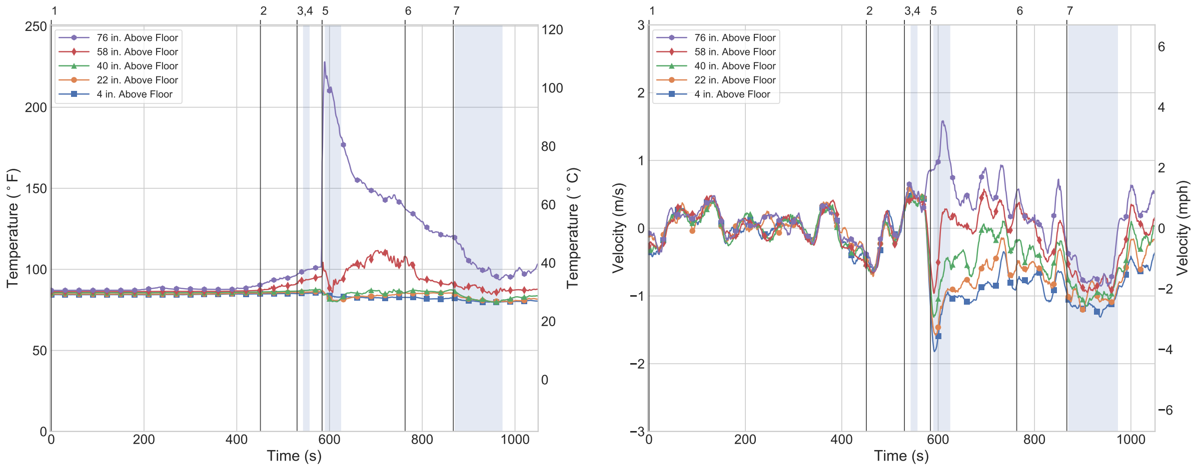


	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

Figure 3.146: Living room gas concentrations for Experiment 4B. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The apartment door was opened 586 s (9:46) post-ignition to allow for the suppression crew to the enter the apartment. Figure 3.147 shows the temperatures and velocities recorded at the fire apartment door. Before the apartment door was opened, smoke leaking past the closed door increased the temperatures at the top two sensors (58 in. and 76 in. above the floor) to over 95 °F. After the apartment door was opened, the temperature at the top sensor increased to 230 °F and flowed out of the apartment at approximately 1.5 m/s (3 mph). At lower elevations, flow was initially into the apartment as the vents in the fire room acted as the predominant exhaust for the higher pressure fire room gases. The gas velocities into the apartment reached peaks between 1 m/s (2 mph) 58 in. above the floor and 2 m/s (4 mph) 4 in. above the floor. The thermocouple at the 58 in. elevation did measure an increase in temperature as the flow became an exhaust during suppression.

Following suppression, gas flow out of the door slowed toward 0 m/s, as the production of combustion gases had stopped. Hydraulic ventilation, which started at 867 s, created unidirectional flow into the apartment through the apartment door at approximately 1 m/s (2 mph).

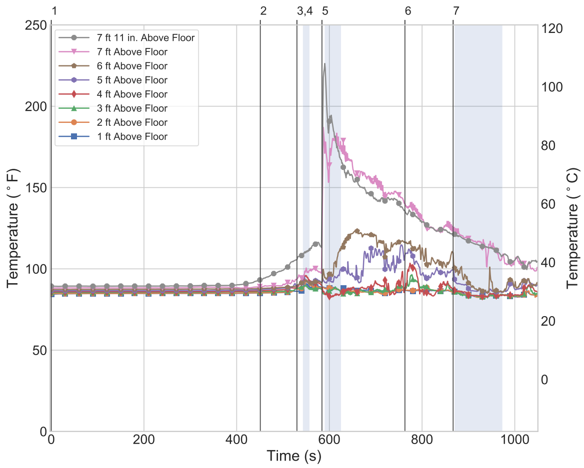


(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

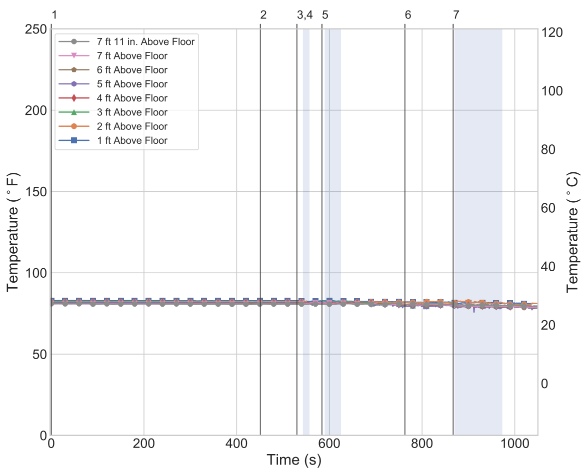
Figure 3.147: Temperatures and velocities at fire apartment (Apartment F) door for Experiment 4B. Blue shaded regions indicate time and duration of water flow.

Temperatures in the stairwell remained ambient and steady (about 85 °F) until 400 s (6:40), when smoke leaking through the closed apartment door began increasing the temperature 1 in. below the ceiling on the second-floor (see Figure 3.148). The temperatures at lower elevations on the second floor remained below 100 °F until the apartment door was opened. The temperatures 1 in. and 1 ft below the ceiling on the second-floor stairwell spiked in response to smoke entering the stairwell when the apartment door was opened, reaching peaks of 225 °F and 185 °F, respectively. Temperatures at 5 ft and 6 ft increased after the apartment door was opened, but did not exceed 125 °F. The second-floor stairwell temperatures gradually decreased after suppression. Hydraulic ventilation increased the rate at which the 5 ft and 6 ft temperatures approached ambient conditions, but did not affect the temperatures 1 in. and 1 ft below the ceiling because those were above the height of the apartment door opening. Temperatures below 5 ft on the second floor and on the lower floors of the stairwell did not exceed 100 °F throughout the experiment.

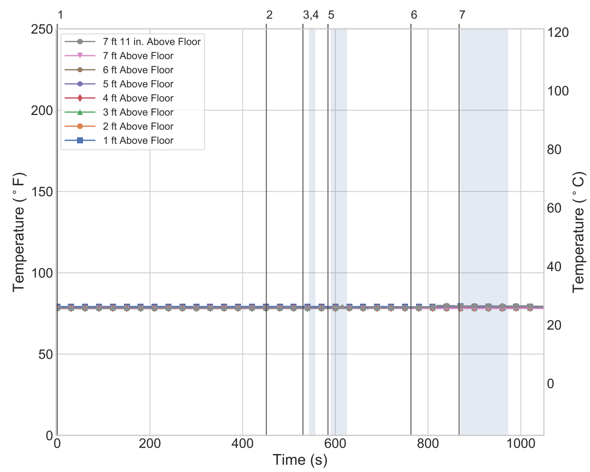


	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

(a) Second-Floor Stairwell



(b) First-Floor Stairwell



(c) Lower-Level Stairwell

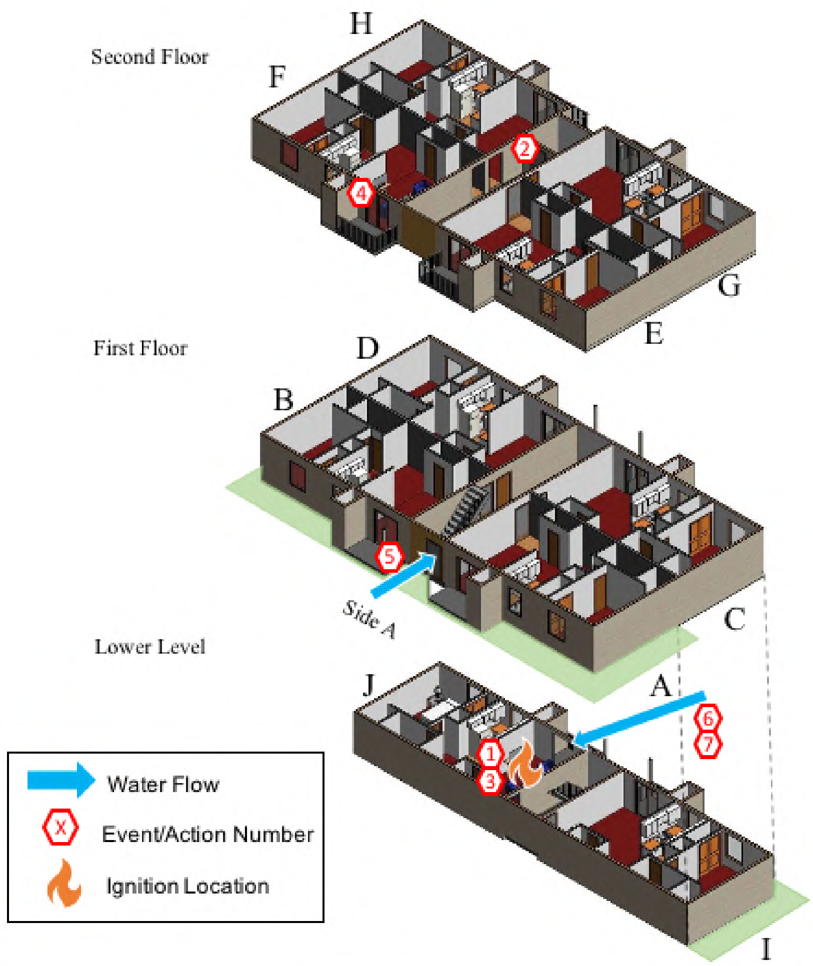
Figure 3.148: Stairwell temperatures for Experiment 4B. Blue shaded regions indicate time and duration of water flow.

Stairwell pressures remained near ambient levels (between -2 Pa and 2 Pa) for the duration of the experiment. The pressures did not respond noticeably to any fire changes or firefighter interventions, including the hydraulic ventilation. Additionally there were no measurable changes to the gas concentrations in the stairwell because the smoke layer on the second floor did not descend below the 5 ft elevation (see Figure 3.148a).

The pressures on each floor of the stairwell were closely aligned throughout the experiment. At 385 s (6:25), the stairwell pressures quickly dropped to -5 Pa, indicating the fire became ventilation-limited. The fire growth after the kitchen window was vented at 451 s (7:31) increased the stairwell pressures to 2 Pa. The stairwell pressures remained near ambient conditions until the start of suppression, when the cooling and contractions of gases caused the stairwell pressure to decrease to -4 Pa. After suppression, the stairwell pressures returned to ambient conditions. Hydraulic ventilation caused the stairwell pressures to decrease to minimums of -4 Pa.

3.12 Experiment 5 – Lower-Level Apartment Fire with Interior Spread

Experiment 5 was conducted in 1972 Kimberly Village Lane SE, and it was designed to evaluate interior fire spread from a lower-level apartment. The fire originated in Apartment J on the lower level, where half of the living room sliding glass door and the apartment door to the stairwell were both open prior to ignition. In addition, the doors from the stairwell to Apartments H and F on the second floor were open. All other exterior windows and doors were closed, including doors to other apartments in the structure. The fire was allowed to grow until it extended from the apartment of origin out into the enclosed stairwell before any firefighter intervention occurred. Firefighter intervention included closing the door to Apartment H and opening half of the sliding glass door in Apartment F. A suppression crew then opened the exterior breezeway door and immediately began interior suppression upon entry. A separate crew applied water from the side C exterior through the fire apartment (Apartment J) living room sliding glass door shortly thereafter. Figure 3.149 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Close Apartment H door	05:41	341
3	Flashover in living room	06:14	374
4	Open Apartment F living room sliding glass door	06:57	417
5	Open exterior door; begin interior suppression	11:27	687
6	Begin exterior water application	12:25	745
7	End exterior water application	16:42	1002

Figure 3.149: Time and sequence of actions and events for Experiment 5.

The experimental volume included the fire apartment (Apartment J) as well as the enclosed stairwell and Apartments F and H on the second floor. The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.150 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

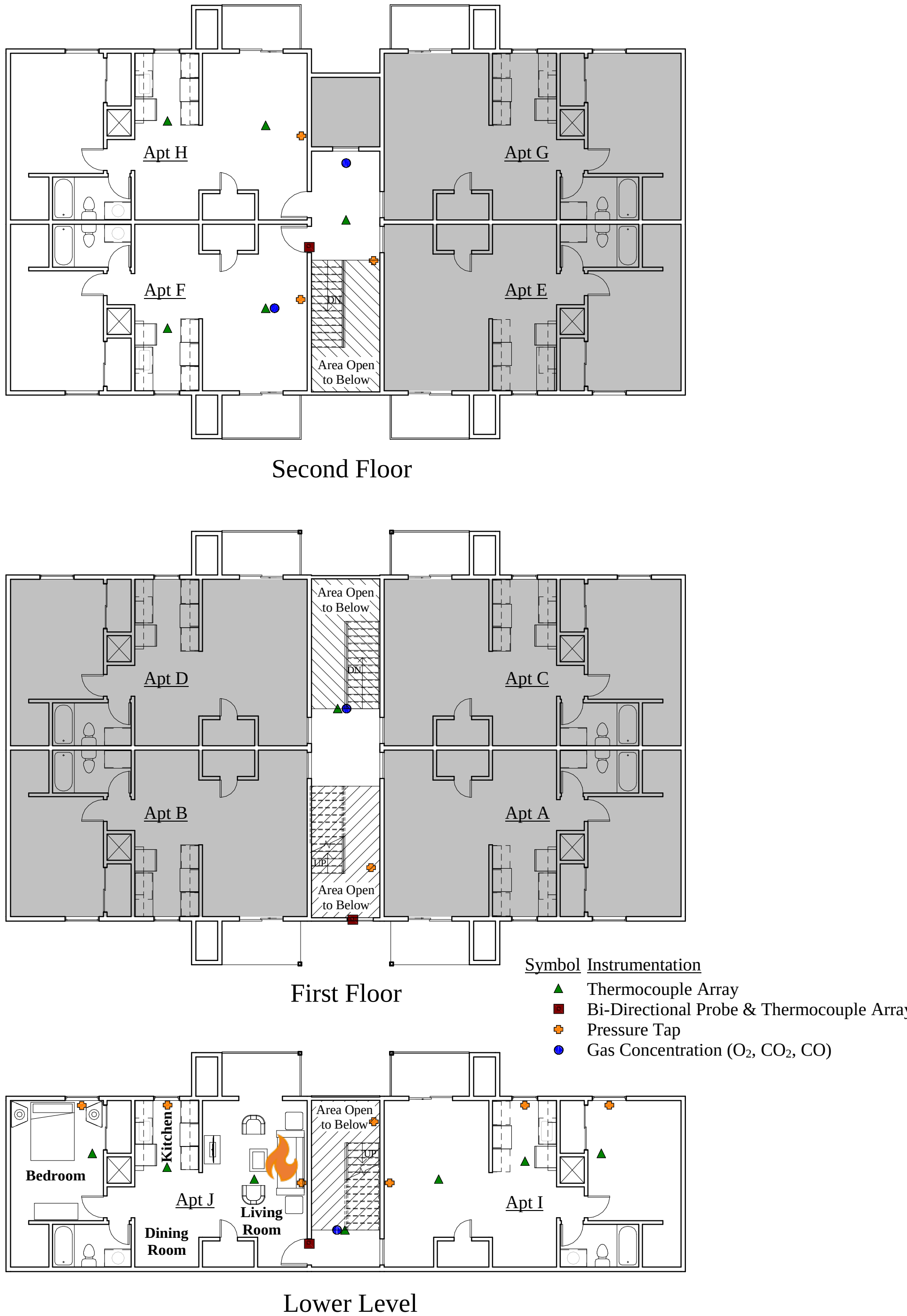


Figure 3.150: Instrumentation locations in Experiment 5.

The living room and kitchen of the apartments included in the experimental volume (Apartments J, F, and H) were furnished with the fuel loads described and photographed in Section 2.5, with the following exceptions. In Apartment F, the living room was furnished with only two barrel chairs and a sofa. In Apartment H, the living room did not have any furniture. Otherwise, the furnishings and their locations in Experiment 5 aligned with the descriptions provided in Section 2.5.

The fire in Experiment 5 was ignited with an electric match placed next to the arm of the sofa in the living room (t = 0 s) of Apartment J. A smoke layer formed throughout the fire apartment, and smoke exhausted out of the open sliding glass door and out of the apartment door into the stairwell. The doors to Apartments F and H on the second floor were open at the start of the experiment, which allowed smoke to flow into both apartments. Smoke was first visible in the second-floor apartments at 222 s (3:42). Flames began extending out of the fire apartment door into the stairwell at 268 s (4:28), and out of the open sliding glass door at 330 s (5:30). By 300 s (5:00), the smoke layer had descended to the floor of the fire apartment, and had filled the stairwell. Zero visibility conditions remained in the fire apartment and the stairwell until fire department interventions occurred. At 377 s (6:17), the fire apartment living room transitioned to flashover.

The first fire department intervention in Experiment 5 was closing the door to Apartment H at 341 s (5:41). The door was closed remotely. The purpose was to examine the effect of isolating an apartment remote from the fire during the fire's growth compared to an apartment left open. A smoke layer had formed in Apartment H prior to closing the door, and it descended to approximately 4 ft above the floor, as shown in Figure 3.151a. Closing the apartment door slowed the rate at which the smoke layer descended, and prevented the smoke layer from reaching the apartment floor.

In Apartment F, the smoke layer descended to the floor at 388 s (6:28). Shortly after, at 417 s (6:57), firefighters opened half of the Apartment F sliding glass door remotely. Smoke immediately began to exhaust out of the sliding glass door and continued to do so until after suppression. Figure 3.151b shows conditions at the sliding glass door immediately after it was opened. There were no flames visible in Apartment F or out of the Apartment F sliding glass door throughout the experiment. Opening the Apartment F sliding glass door created a low-pressure exhaust vent above the fire, which led to additional intake flows in the fire apartment.

(a) Apartment H Living Room When the Door to the Apartment Was Closed (341 s)

(b) Apartment F Sliding Glass Door 5 s after Being Opened (422 s)

Figure 3.151: Images of the conditions in the second-floor apartments (Apartments H and F) during ventilation changes in Experiment 5.

Firefighters opened the exterior breezeway door at 687 s (11:27) and immediately began suppression in the stairwell using a 7/8 in. smooth bore nozzle attached to 200 ft of 1 3/4 in. hoseline, and flowing at 160 gpm. The nozzle was operated in an O pattern from a fixed position. The crew attempted to advance into the structure toward the fire apartment on the lower-level, but could not initially make progress due to heat in the stairwell. The crew maintained their position near the top of the lower-level stairs while flowing water. During this time, a separate crew on side C began flowing water from the exterior into the fire apartment living room at 745 s (12:25, see Figure 3.152a). The exterior crew used a combination nozzle and flowed 150 gpm. The exterior water application from side C continued for 86 s with a stationary stream as to not occlue the ventilation opening. Water was deflected off of the sliding glass door frame and living room wall. The exterior crew then stopped flowing water, used 30 s to reposition closer to the structure, then flowed water for an additional 141 s (see Figure 3.152b). The second application of water was a steeper approach with water deflected off the ceiling, limiting manipulation as to avoid occlusion. Total water flowed from the exterior was estimated at 568 gallons.

(a) Start of Exterior Water Application (745 s)

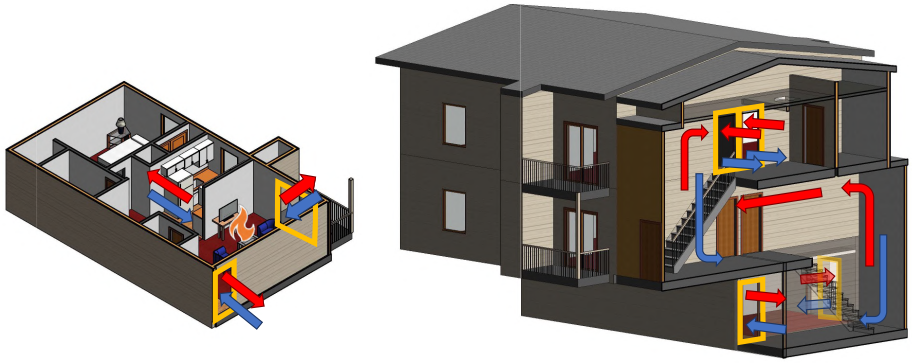
(b) Start of Exterior Water Application after Repositioning (860 s)

Figure 3.152: Images of the conditions on the side C exterior during exterior water application in Experiment 5.

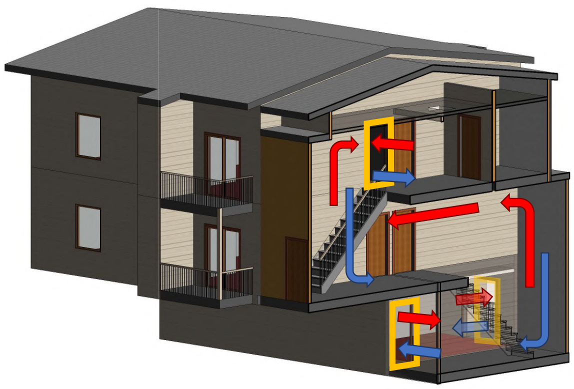
The exterior water application successfully knocked down the fire in the fire apartment. This improved conditions in the structure such that the interior suppression crew could continue their advance down the interior stairs to the fire apartment, which began at about 821 s (13:41). The interior suppression crew continued flowing water throughout their advance, and after entering the fire apartment 1032 s (17:12) post-ignition. The initial interior suppression operation continued until 1129 s (18:49), lasting a total of 443 s (7:23), with the crew flowing 975 gallons of water. Any water flow after the initial interior suppression operation ended at 1129 s (18:49) was utilized during overhaul operations.

The flow of combustion gases and fresh air during Experiment 5 are sketched in Figure 3.153. As the fire grew in the living room of Apartment J, high-temperature, lower density fire gases rose and began to fill the fire compartment from the top down. The kitchen was open to the living room, therefore the common space filled simultaneously. Once the hot gas layer reached the top of the sliding glass door in the living room, gases began exhausting to the environment. At the same time, gases exhausted out of the upper portion of the apartment door and rose through the stairwell due to buoyancy. Entrainment from the fire plume drew air through the lower portions of the sliding glass door and apartment door into the fire compartment, which led to further fire growth. A hot gas layer formed in the stairwell that descended below the tops of the second-floor apartment doors. The doors to Apartments F and H on the second floor were open, allowing smoke in the stairwell to enter those apartments (see Figure 3.153a).

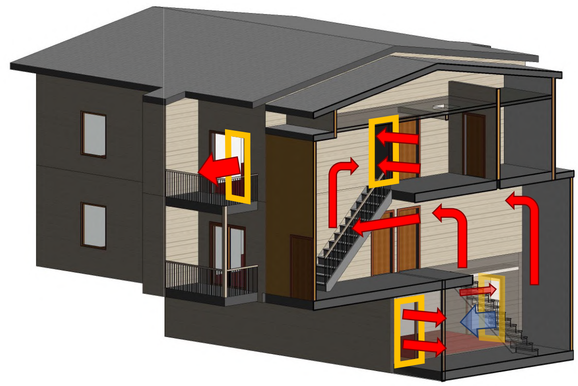
The Apartment H door was closed 341 s (5:41) after ignition, preventing further accumulation of smoke in the apartment (see Figure 3.153b). About 60 s later, the Apartment F sliding glass door was opened, creating a flow path through the stairwell. The open sliding glass door on the second floor served as a new low-pressure exhaust vent above the level of the fire. The buoyant fire gases from below rose through the stairwell, through Apartment F, and out of the sliding glass door to the lower pressure atmosphere. As gas flow through the stairwell increased, there was a corresponding increase in intake flow through the sliding glass door in the fire apartment (see Figure 3.153c). Firefighters then opened the exterior breezeway door to begin interior suppression. The open door provided a new exhaust for the flow of fire gases through the stairwell. Additionally, cooler, ambient air was entrained into the structure through the bottom of the door (see Figure 3.153d). Shortly thereafter, an exterior stream was applied to the fire apartment from side C of the structure. In combination, these two suppression methods knocked down the fire, which stopped the production of combustion gases.



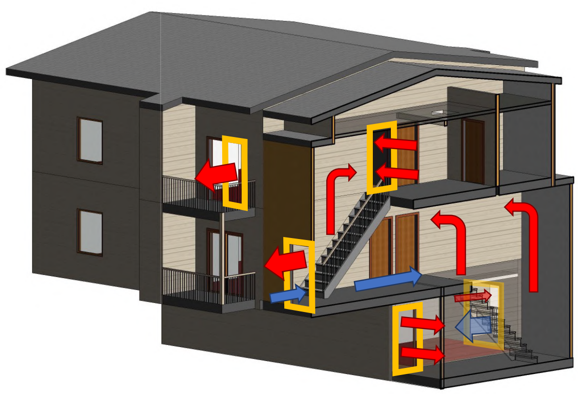
(a) Prior to Any Ventilation Changes



(b) After Closing Apt. H Door



(c) After Opening Apt. F Sliding Glass Door

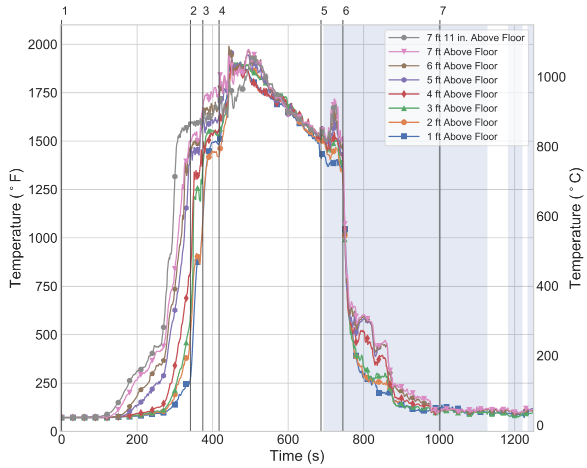


(d) After Opening the Exterior Breezeway Door and Starting Interior Suppression

Figure 3.153: Changes in flow during Experiment 5. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

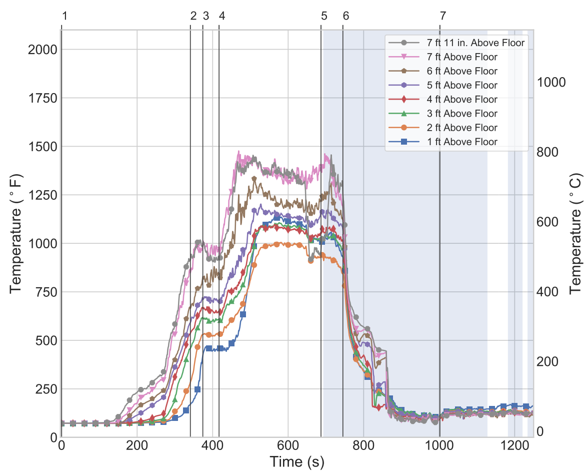
The time histories of the temperatures in the fire apartment are presented in Figure 3.154. The temperature near the living room and kitchen ceilings began to increase 120 s (2:00) post ignition, and the living room transitioned to flashover (i.e., temperatures at all elevations exceeded 1100 °F) by 374 s (6:14). At 417 s, when an exhaust was created (opening Apartment F sliding glass door), the temperatures further increased as the vent above the fire improved the intake efficiency of the fire apartment vent. The peak living room temperatures were between 1800 °F and 2000 °F at all elevations. Living room temperatures began to decrease as the fire became ventilation-limited, but rose to between 1500 °F to 1700 °F following the opening of the breezeway door. The open door had a similar impact as the Apartment F sliding glass door despite the suppression crew flowing water in the stairwell. The living room remained in a post-flashover state until the start of exterior water application at 745 s (12:25), which quickly reduced the living room temperatures.

Temperatures in the kitchen of the fire apartment increased until the living room reached flashover, at which point temperatures became steady. The temperatures at that time ranged between 445 °F 1 ft above the floor to 1020 °F 1 in. below the ceiling. At 417 s (6:57), the Apartment F sliding glass door was opened, creating a flow path through the stairwell. In response to the additional ventilation, the kitchen temperatures began to increase. The kitchen temperatures rose until 530 s (8:50), then became steady as the fire reached the limits of the new ventilation configuration. The temperatures ranged between 1005 °F 2 ft above the floor to 1480 °F 1 in. below the ceiling. The kitchen temperatures increased in response to the breezeway door being opened and remained elevated until the start of exterior water application at 745 s (12:25), which quickly reduced the kitchen temperatures. Within 120 s, temperatures at all elevations in the kitchen were below 200 °F.

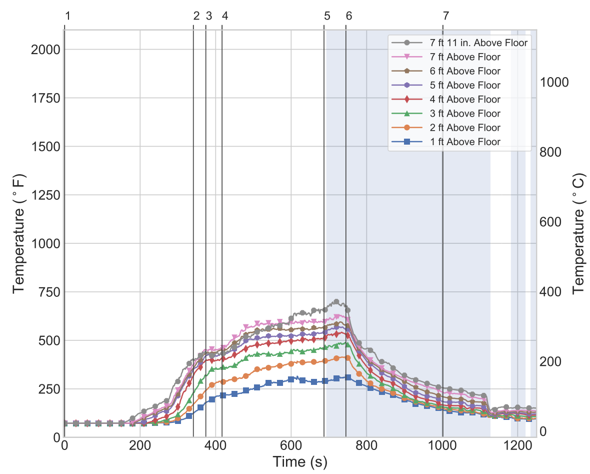


(a) Living Room

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002



(b) Kitchen

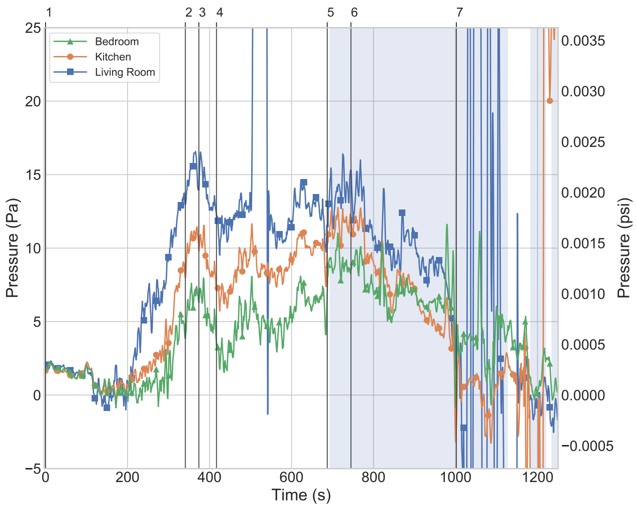


(c) Bedroom

Figure 3.154: Fire apartment (Apartment J) temperatures for Experiment 5. Blue shaded regions indicate time and duration of water flow.

Temperatures in the bedroom of the fire apartment remained lower than in the kitchen or living room due to the bedroom's distance from the origin of the fire, and its location outside of a flow path between the fire and a vent. The temperature near the ceiling in the bedroom began increasing at 150 s (2:30). The bedroom temperature increased gradually, reaching a peak immediately prior to exterior water application. The peak bedroom temperatures ranged between 315 °F 1 ft above the floor to 705 °F 1 in. below the ceiling. The bedroom temperature then steadily declined after the start of exterior water application due to knock down of the fire.

The pressure measurements in the fire apartment were closely aligned and reflect the growth stages of the fire (see Figure 3.155). The pressures in each room began increasing at 200 s (3:20) as the fire grew. The peak pressures, at 360 s (6:00), were 17 Pa in the living room, 12 Pa in the kitchen, and 8 Pa in the bedroom. The pressures then decreased, indicating the fire became ventilation-limited. The minimum pressures during this time window were 10 Pa in the living room, 6 Pa in the kitchen, and 2 Pa in the bedroom. When the Apartment F sliding glass door was opened at 417 s (6:57), the fire growth due to the additional ventilation caused pressures in the fire apartment to increase. The pressures continued increasing until the start of exterior water application at 745 s (12:25), reaching peaks of 17 Pa in the living room, 13 Pa in the kitchen, and 11 Pa in the bedroom. After knock down of the fire due to the exterior water application, the fire apartment pressures began steadily decreasing toward ambient conditions.

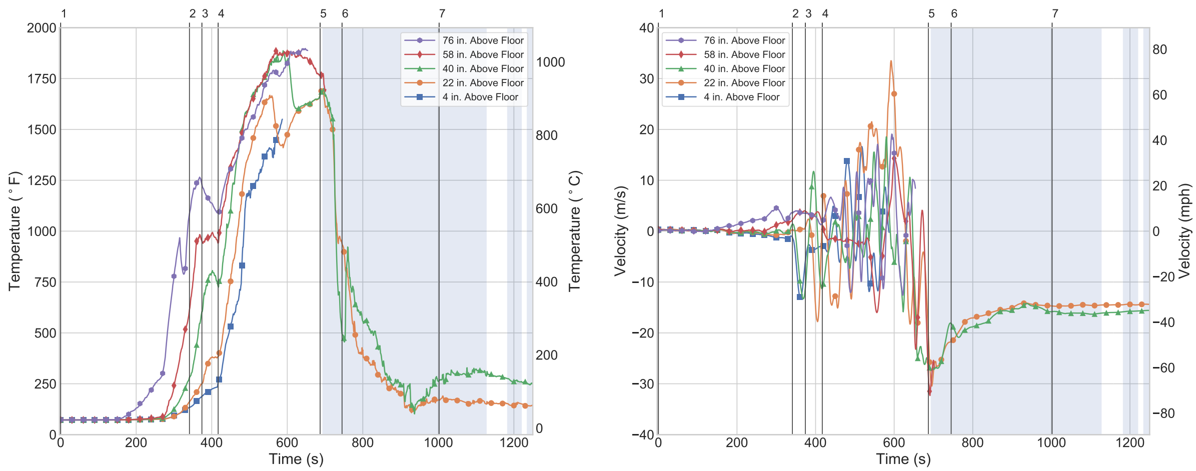


	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.155: Fire apartment pressures for Experiment 5. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The temperature and gas velocity were measured at the fire apartment (Apartment J) door (see Figure 3.156). Smoke began exhausting through the top of the door at approximately 135 s (2:15). The velocity at the top sensor (76 in. above the ground) increased to a peak of 4.5 m/s (10 mph) by 300 s (5:00), at which time the temperature exceeded 750 °F and continued increasing. There was also exhaust at the 58 in. elevation, but at lower temperature and velocity. At the 22 in. and 4 in. elevations, air was entrained into the fire apartment at approximately 1 m/s (2 mph). The temperature at those elevations increased despite the inflow due to heat transfer from the hot gases exhausting through the top of the doorway.

As the living room transitioned to flashover at 374 s (6:14), gases at the 76 in. and 58 in. elevations continued exhausting from the apartment at 3 m/s (7 mph) to 4 m/s (9 mph). Gases at lower elevations became mixed, oscillating between intake and exhaust from the apartment. The temperatures at all elevations increased at an accelerated rate. The Apartment F sliding glass door was opened at 417 s (6:57), forming a flow path through the stairwell between the fire apartment and Apartment F. Gas mixing at the fire apartment door increased as velocities at all elevations oscillated between intake at up to 18 m/s (40 mph) and exhaust at up to 34 m/s (76 mph). The temperatures increased to peaks between 1500 °F and 1900 °F. Between 585 s (9:45) and 700 s (11:40), the sensors at the 4 in., 58 in., and 76 in. elevations became damaged, so data from those sensors is omitted from Figure 3.156 after those times. After the start of exterior water application at 745 s (7:25), thermocouple temperatures at the apartment door decreased. Gas contraction in the fire apartment due to the temperature drop entrained air into the apartment at peaks of 27 m/s (60 mph) at the 40 in. elevation and 30 m/s (67 mph) at the 22 in. elevation. The velocities then settled between 14 m/s (31 mph) and 16 m/s (36 mph) as gases continued moving from the stairwell to the vents in the fire apartment.



(a) Temperature (b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

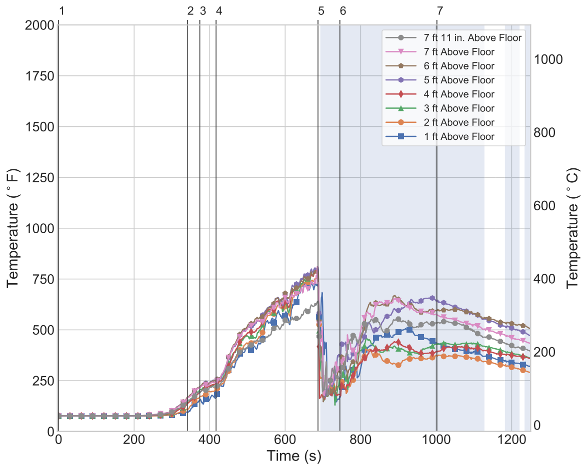
Figure 3.156: Temperatures and velocities at Apartment J door for Experiment 5. Between 585 s (9:45) and 700 s (11:40), the sensors at the 4 in., 58 in., and 76 in. elevations became damaged, so data from those sensors is omitted thereafter. Blue shaded regions indicate time and duration of water flow.

The time histories of the temperature in the stairwell are presented in Figure 3.157. The temperatures began increasing at 150 s (2:30) on the lower level, 180 s (3:00) on the first floor, and 260 s (4:20) on the second floor. At 417 s (6:57) the Apartment F sliding glass door was opened, creating a flow path through the stairwell.

The low-pressure vent above the fire was an efficient exhaust vent because the buoyant, elevated-pressure fire gases rose and flowed toward areas of lower pressure. Additional exhaust out of the fire apartment also increased the intake efficiency of the open vents. This led to an increased heat release rate and, therefore, higher temperatures. Essentially, the stairwell became a chimney. Temperatures on the lower level increased until 565 s (9:25), then reached a peak and remained steady until the start of suppression. The peak temperatures ranged between 1600 °F and 1800 °F at all elevations on the lower level. On the first and second floors, the temperatures continued increasing until the start of suppression. The peak temperatures were between 1300 °F and 1450 °F on the first floor and between 640 °F and 810 °F on the second floor.

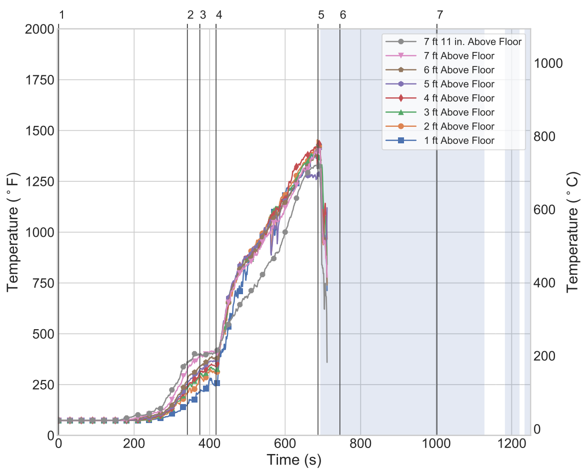
At 687 s (11:27), the suppression crew opened the exterior breezeway door and began suppression, which reduced temperatures on all floors of the stairwell. The thermocouple array on the first floor was impacted by the hose stream during suppression, so data from that array is omitted after 712 s (11:52).

The lower-level stairwell temperatures dropped to a range of 185 °F to 350 °F, and the second floor dropped to a range of 175 °F to 215 °F due to the water flow from the interior suppression crew. Water flow from the stairwell did not impact the fire apartment (see Figure 3.154) and combustion gases continued to flow into the stairwell. The stairwell temperatures then recovered slightly, 340 °F to 630 °F on the lower level and 375 °F to 635 °F on the second floor. Following the exterior suppression action and continued interior suppression actions, the stairwell temperatures decreased toward ambient conditions for the remainder of the experiment.

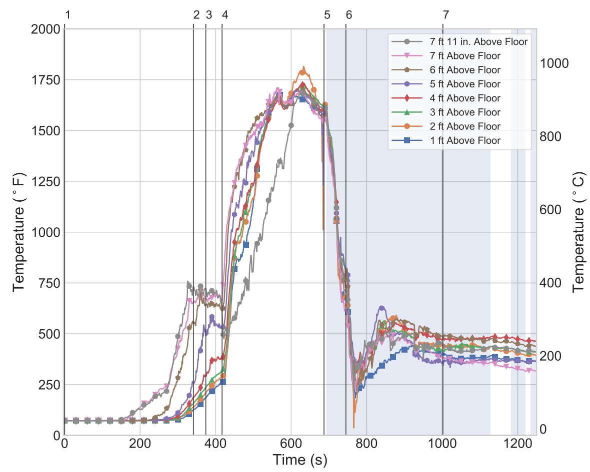


(a) Second-Floor Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002



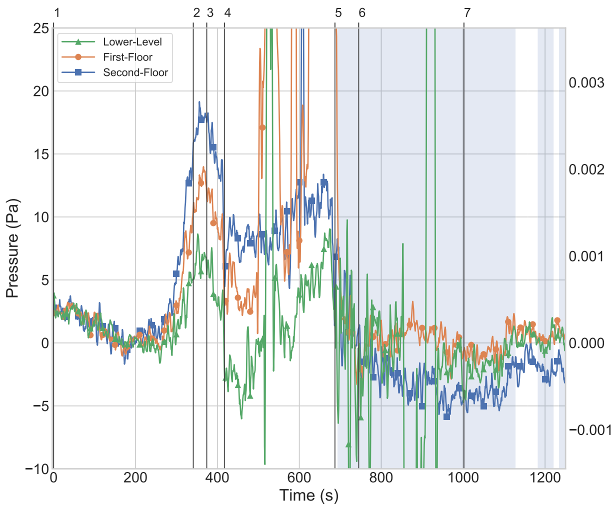
(b) First-Floor Stairwell



(c) Lower-Level Stairwell

Figure 3.157: Stairwell temperatures for Experiment 5. The first-floor thermocouple was impacted by the hosestream during suppression at around 700 s (11:40), so data thereafter is omitted. Blue shaded regions indicate time and duration of water flow.

The time histories of the pressures in the stairwell are shown in Figure 3.158. The stairwell pressures began increasing at 270 s (4:30), approximately the same time as flames started extending into the stairwell from the fire apartment. The stairwell pressures continued increasing and reached a peak at 360 s (6:00). The peak coincided with the peak in fire apartment pressures. The peak stairwell pressures were 19 Pa on the second floor, 14 Pa on the first floor, and 9 Pa on the lower level. The stairwell pressures decreased when the Apartment F sliding glass door was opened at 417 s (6:57), reaching minimums of 5 Pa on the second floor, 2 Pa on the first floor, and -6 Pa on the lower level. Opening the Apartment F sliding glass door created a flow path through the stairwell, which led to an increase in heat release rate in the fire apartment and caused the stairwell pressures to slowly increase. At 526 s, the lower-level and first-floor pressures reached another local peak before firefighters opened the exterior door and began interior suppression at 687 s (11:27), releasing smoke from the stairwell and cooling the gases. In response, the stairwell pressures dropped toward ambient conditions.

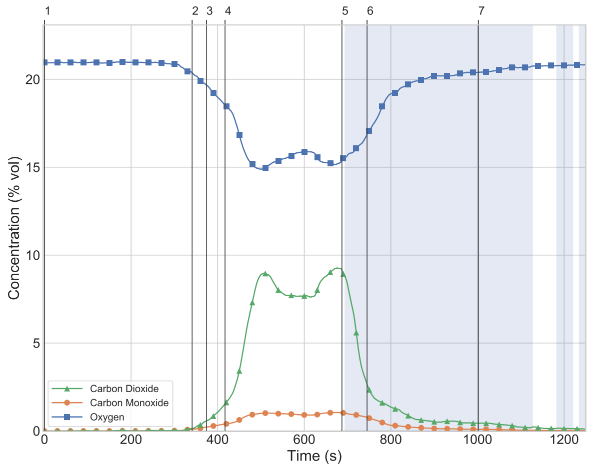


	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.158: Stairwell pressures for Experiment 5. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

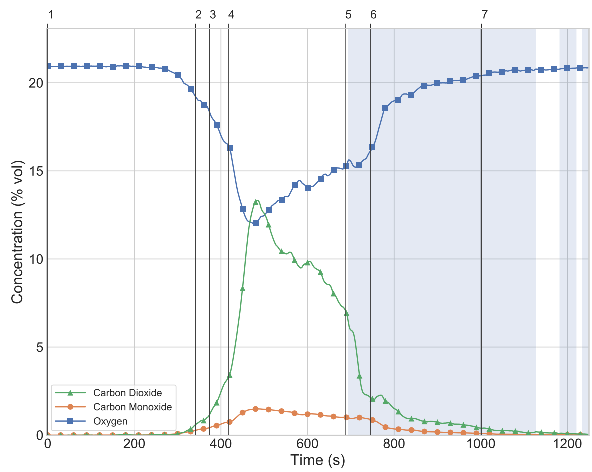
The time histories of the gas concentrations measured in the stairwell are presented in Figure 3.159. The lower-level instrument location was damaged from the beginning of the experiment, so those data are omitted. Gas concentrations first began to change on the first floor at 230 s as smoke moved up the stairwell past the instrument location. The second-floor gas concentrations began to change at 305 s as the smoke layer descended in the stairwell. The increase in heat release rate of the fire (due to the flow path created through the stairwell by opening the Apartment F sliding glass door) led conditions in the stairwell to further deteriorate. The O_2 concentration on the first floor fell below 15% at 430 s (3:25), which limited fire extension through the stairwell. The stairwell gas concentrations reached local peaks between 480 s (8:00) and 500 s (8:20). The peak concentrations were 12.0% O_2, 13.4% CO_2, and 1.5% (15,000 ppm) CO on the first floor and 14.8% O_2, 9.0% CO_2, and 1.0% CO (10,000 ppm) on the second floor.

Conditions on the first floor of the stairwell steadily improved while the second-floor gas concentrations remained relatively steady. When the exterior door was opened and firefighters began interior suppression at 687 s (11:27), gas concentrations on each floor of the stairwell began improving. The rate of improvement was accelerated when exterior water application began at 745 s (12:25). Gas concentrations in the stairwell steadily returned to ambient conditions for the remainder of the experiment.



	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

(a) Second-Floor Stairwell

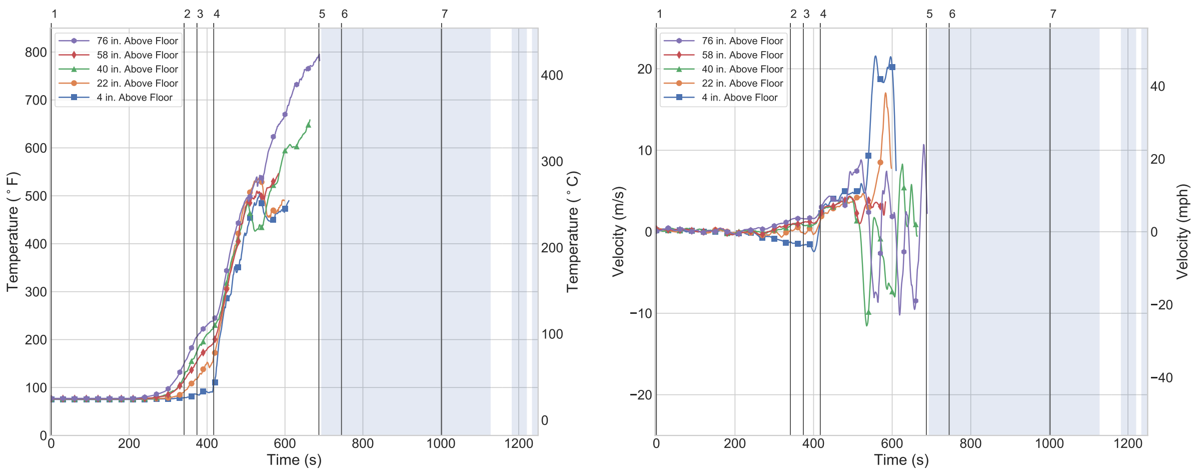


(b) First-Floor Stairwell

Figure 3.159: Stairwell gas concentrations for Experiment 5. The lower-level measurement probe was damaged from the start of the experiment, so data from that sensor is omitted. Measurement locations were 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The temperature and gas velocity were measured at the Apartment F door (see Figure 3.160). By around 300 s (5:00), the top sensor measured an increase in temperature and velocity as smoke began entering the apartment. The smoke layer continued to descend until the Apartment F sliding glass door was opened at 417 s (6:57). Prior to that time, sensors at the 40 in. elevation and above measured 2 m/s (4 mph) to 3 m/s (7 mph) flow into the apartment, and temperatures above 200 °F. At the 22 in. elevation, the gas velocity remained near 0 m/s, indicating its proximity to the neutral plane. Ambient-temperature air 4 in. above the floor exhausted from the apartment at over 2 m/s (4 mph).

The flow into the apartment became unidirectional when the Apartment F sliding glass door was opened, providing an exhaust for the flow path through the stairwell. The gas velocities ranged between 3 m/s (7 mph) and 5 m/s (11 mph), and the temperature increase accelerated. At approximately 480 s (8:00), the flow into Apartment F transitioned from unidirectional to mixed as the volume of smoke overwhelmed the capacity of the sliding glass door to vent. At the 4 in. and 22 in. elevations, the gas velocities into the apartment accelerated to peaks of 22 m/s (49 mph) and 17 m/s (38 mph), respectively. At the 40 in. elevation and above, the velocities began oscillating between intake at 11 m/s (25 mph) and exhaust at 13 m/s (29 mph). Between 480 s (8:00) and 720 s (12:00), each of the sensors were damaged, so data thereafter is omitted.



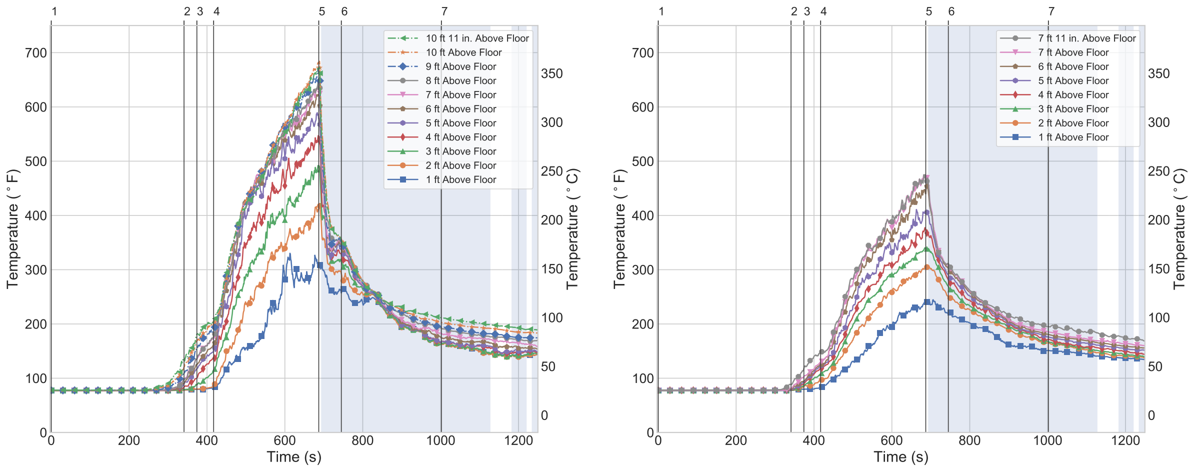
(a) Temperature

(b) Velocity

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.160: Temperatures and velocities at Apartment F door for Experiment 5. Data after 720 s (12:00) is omitted because the sensors were impacted by water from suppression. Blue shaded regions indicate time and duration of water flow.

The time histories of the Apartment F kitchen and living room temperatures are presented in Figure 3.161. The temperature near the ceiling in the living room began increasing at 250 s (4:10). As the smoke layer descended, temperatures above 2 ft increased, while temperatures at 1 ft and 2 ft above the floor remained near ambient conditions (75 °F). At 374 s (6:14), the sliding glass door was opened, creating a flow path from the fire room through the stairwell to Apartment F. Temperatures at all elevations in Apartment F immediately began to increase in response. They continued increasing until firefighters opened the exterior door and began interior suppression at 687 s (11:17). At that time, the peak temperatures for all elevations ranged between 310 °F and 685 °F in the living room and 240 °F and 475 °F in the kitchen. The temperature in Apartment F immediately decreased at the start of suppression, and continued decreasing toward ambient conditions thereafter.

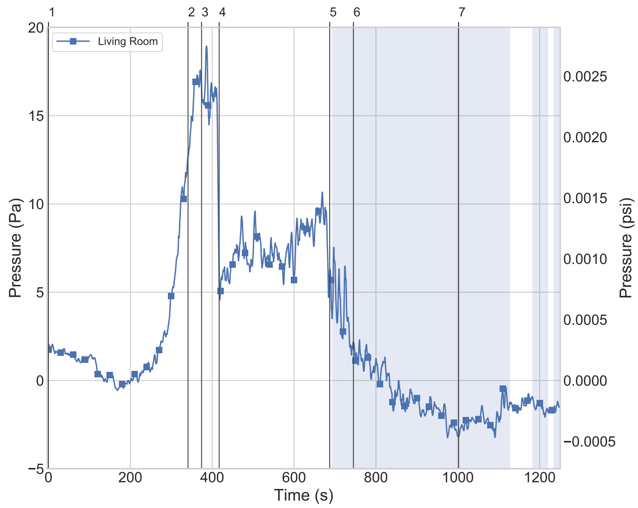


(a) Living Room (b) Kitchen

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.161: Apartment F temperatures for Experiment 5. Blue shaded regions indicate time and duration of water flow.

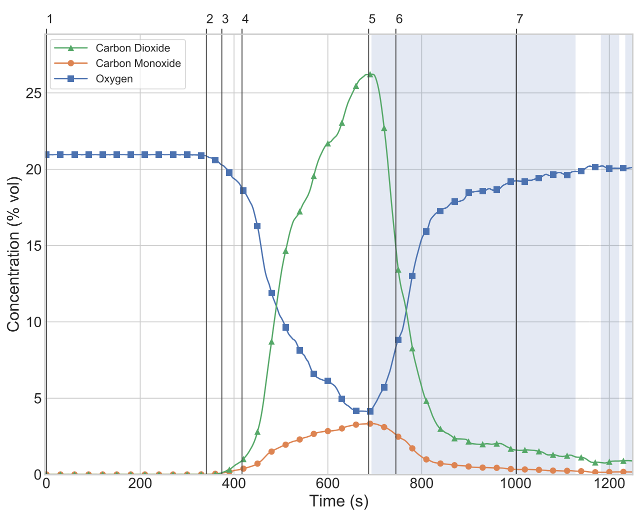
The time histories of the living room pressure in Apartment F is shown in Figure 3.162. At approximately 200 s (3:20), the pressure began increasing as smoke filled the room. The pressure continued to increase, reaching a peak of 19 Pa at 360 s (6:00). This time corresponds to when the fire became ventilation-limited. The pressure remained near 17 Pa until the Apartment F sliding glass door was opened at 417 s (6:57), releasing smoke from the apartment. The pressure quickly dropped to 5 Pa, then began a slow increase as hot gases flowed from the fire apartment on the lower level to Apartment F. At 687 s (11:27), the exterior door was opened and firefighters began interior suppression. At that time, the pressure in Apartment F had reached 11 Pa, but it dropped in response to cooling and ventilation provided by the firefighters.



	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.162: Apartment F pressure for Experiment 5. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

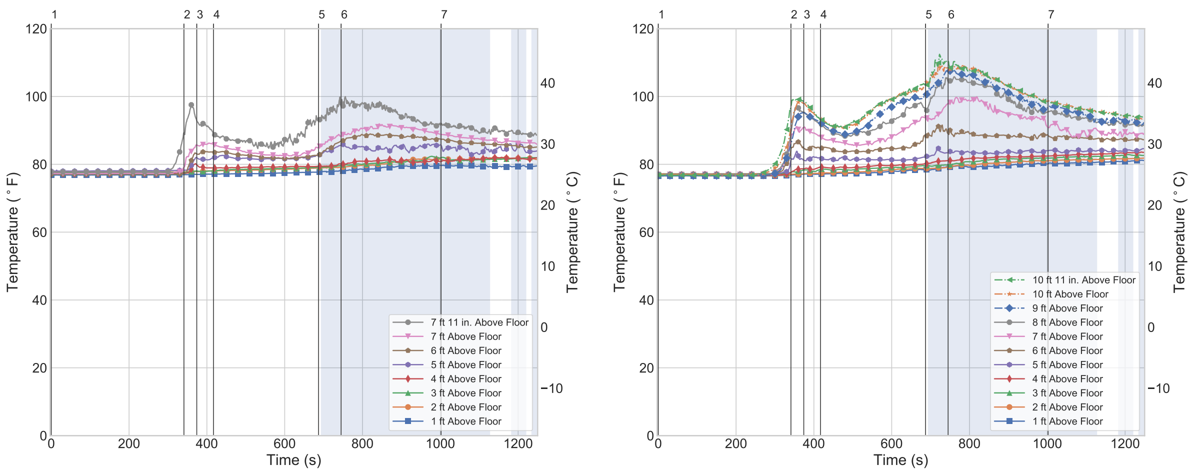
Gas concentrations were measured in the living room of Apartment F (Figure 3.163). Gas concentrations began to change in response to the smoke layer forming in the apartment at 360 s (6:00). The O_2 concentration fell below 15% at 458 s (7:38), which is why no flaming combustion occurred despite the high temperatures. Conditions in Apartment F continued to steadily decline until 687 s (11:27), when the exterior door was opened and interior suppression began. At that time, the O_2 concentration reached a minimum of 4.1%, and the CO and CO_2 concentrations reached maximums of 3.4% (34,000 ppm) and 26.2%, respectively. Then conditions began to improve. By the time exterior water application ended at 1002 s (16:42), the gas concentrations were 19.3% O_2, 0.3% CO (3000 ppm), and 1.6% CO_2.



	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.163: Living room gas concentrations in Apartment F for Experiment 5. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

The time histories of the Apartment H kitchen and living room temperature are presented in Figure 3.164. The temperature near the ceiling in the living room began increasing at 270 s (4:30). The temperatures throughout Apartment H became stratified between 4 ft and 5 ft, an indication of the height of the smoke layer throughout the apartment. Temperatures above 4 ft increased, reaching peaks between 80 °F and 100 °F, while temperatures at 4 ft and below remained near ambient conditions (75 °F). The peaks occurred at 341 s (5:41) as the apartment door was shut, isolating Apartment H from the rest of the structure. The temperatures in the smoke layer temporarily decreased for 140 s, then began gradually increasing again after the sliding glass door to Apartment F was opened. The temperatures above 4 ft in Apartment H reached peaks between 85 °F and 115 °F. After the start of interior suppression at 687 s (11:27), the Apartment H temperatures began gradually decreasing toward ambient conditions. Temperatures below 5 ft in Apartment H slowly increased throughout the experiment, but did not exceed 85 °F.

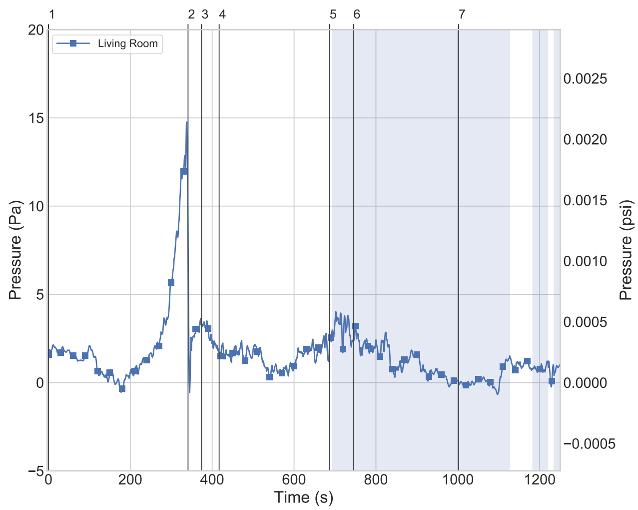


(a) Kitchen (b) Living Room

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.164: Apartment H temperatures for Experiment 5. Blue shaded regions indicate time and duration of water flow.

The time history of the pressure in Apartment H is shown in Figure 3.165. Similar to Apartment F and the stairwell, the pressure began increasing at approximately 200 s (3:20) due to the build up of combustion gases from the fire apartment and no exhaust. At 341 s (5:41), the door to Apartment H was closed and the pressure dropped because the apartment was isolated from the stairwell. The pressure settled to 2.5 Pa based on the amount of combustion gases that had filled the space prior to the door being closed. Pressure declined to 0 Pa following suppression as gas temperatures cooled.

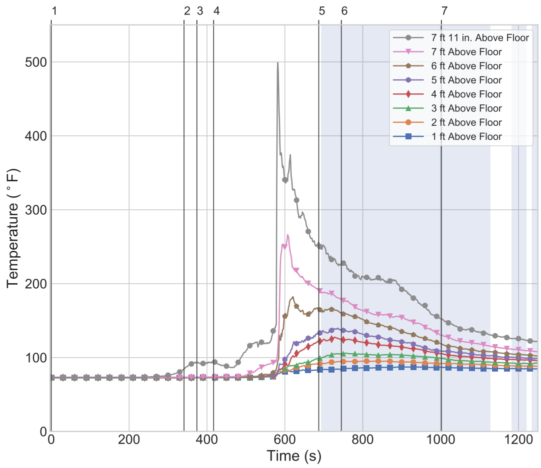


	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.165: Apartment H pressure for Experiment 5. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

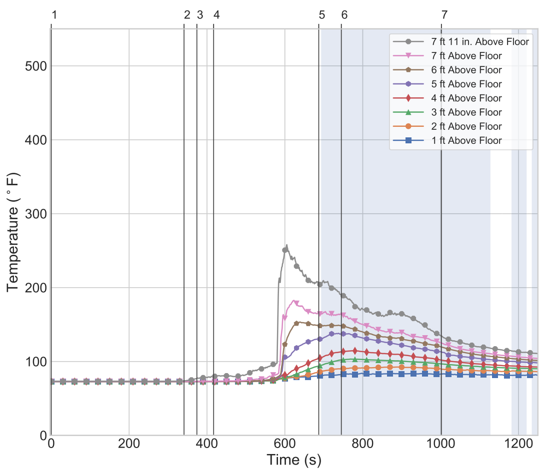
The time histories of the Apartment I temperatures are presented in Figure 3.166. Apartment I was on the lower level, directly across the stairwell from the fire apartment. The door to Apartment I remained closed for the duration of the experiment. For the first 500 s, temperatures throughout the apartment remained below 100 s, after which temperatures at the ceiling in the living room and kitchen began in increase.

At 575 s, temperatures throughout the apartment increased, likely due to combustion gases flowing into the apartment through gaps around the door as a result of a sufficient pressure difference between the stairwell (i.e., high pressure) and the apartment (i.e., low pressure). The living room temperatures began to decrease less than 10 s later, an indication that gases did not steadily flow into the apartment. The lower-level temperatures in the stairwell at that time were greater than 1300 °F at all elevations. The temperature in Apartment I reached a peak of 500 °F, measured 1 in. below the ceiling in the living room. Temperatures measured below 6 ft above the floor throughout the apartment, however, did not exceed 140 °F.

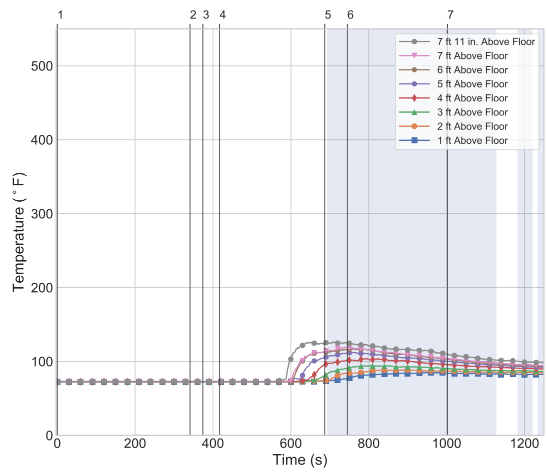


(a) Living Room

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002



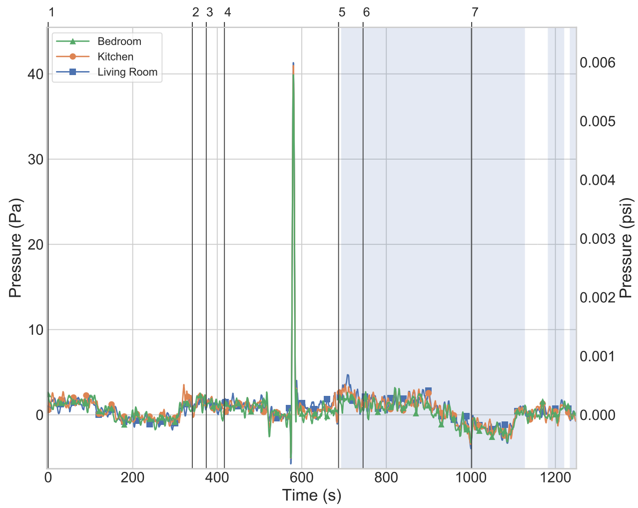
(b) Kitchen



(c) Bedroom

Figure 3.166: Apartment I temperatures for Experiment 5. Blue shaded regions indicate time and duration of water flow.

The time history of the pressure in Apartment I is shown in Figure 3.167. At 575 s, a momentary pressure spike of approximately 40 Pa was measured at all three locations. The pressure rise occurred at the same time as the temperatures rise, which confirms the flow of gases into the apartment. The pressure then returned to ambient conditions as flow into the apartment slowed.

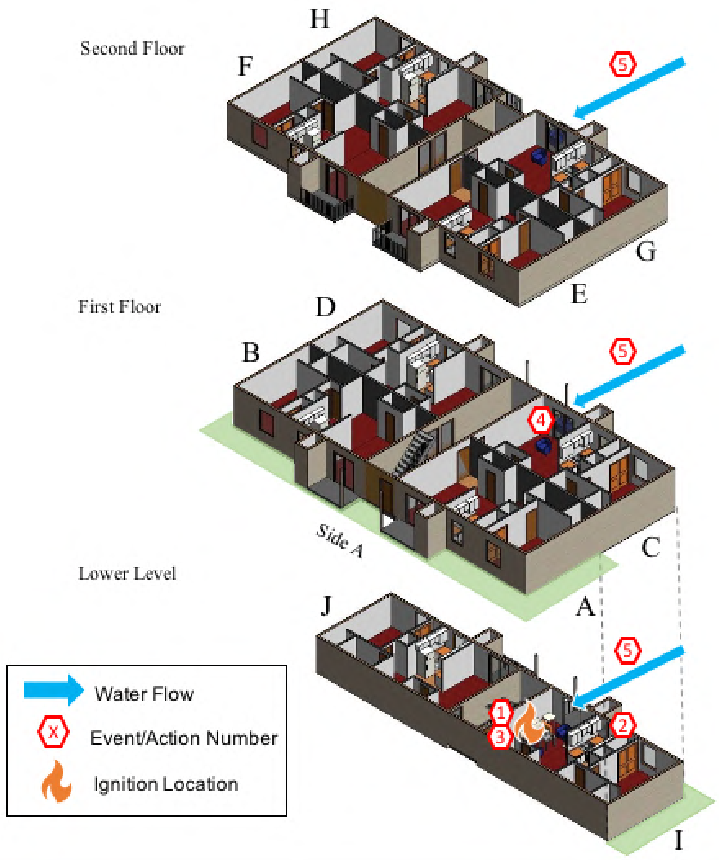


	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

Figure 3.167: Apartment I pressure for Experiment 5. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

3.13 Experiment 6 – Lower-Level Apartment Fire with Exterior Spread

Experiment 6 was conducted in 1972 Kimberly Village Lane SE, and it was designed to evaluate exterior fire spread from a lower-level apartment. The fire originated in Apartment I on the lower level, with the bedroom door closed and half of the living room sliding glass door open prior to ignition. Half of the living room sliding glass door to the second-floor apartment two-floors directly above the fire apartment (Apartment G) was also open. All other exterior windows and doors were closed, including the fire apartment door and doors to other apartments in the structure. The fire was allowed to grow until it extended from the apartment of origin to the apartments directly above via the exterior wooden balcony structures before any suppression occurred. Firefighter intervention included venting the kitchen window of the fire apartment, followed by exterior fire control. The sliding glass door in the first-floor apartment above the fire apartment (Apartment C) failed prior to suppression. Figure 3.168 shows the sequence of events in the experiment and corresponding locations within the structure.



	Action/Event	Time (mm:ss)	Time (s)
1	Ignition	00:00	0
2	Vent kitchen window	07:41	461
3	Flashover in living room	08:35	515
4	Apartment C (first-floor) sliding door failed	10:45	645
5	Begin exterior water application from side C	10:56	656

Figure 3.168: Time and sequence of actions and events for Experiment 6.

The experimental volume included the fire apartment (Apartment I) as well as the first- and second-floor apartments directly above the fire apartment (Apartments C and G, respectively). The structure was instrumented for temperature, gas concentration, velocity, pressure, and video (thermal imaging and standard) to capture the fire dynamics and firefighter intervention during the experiment. Figure 3.169 shows the layout of the experimental volume with the instrumentation locations. Grey shaded regions indicate areas within the structure that were not considered part of the experimental volume.

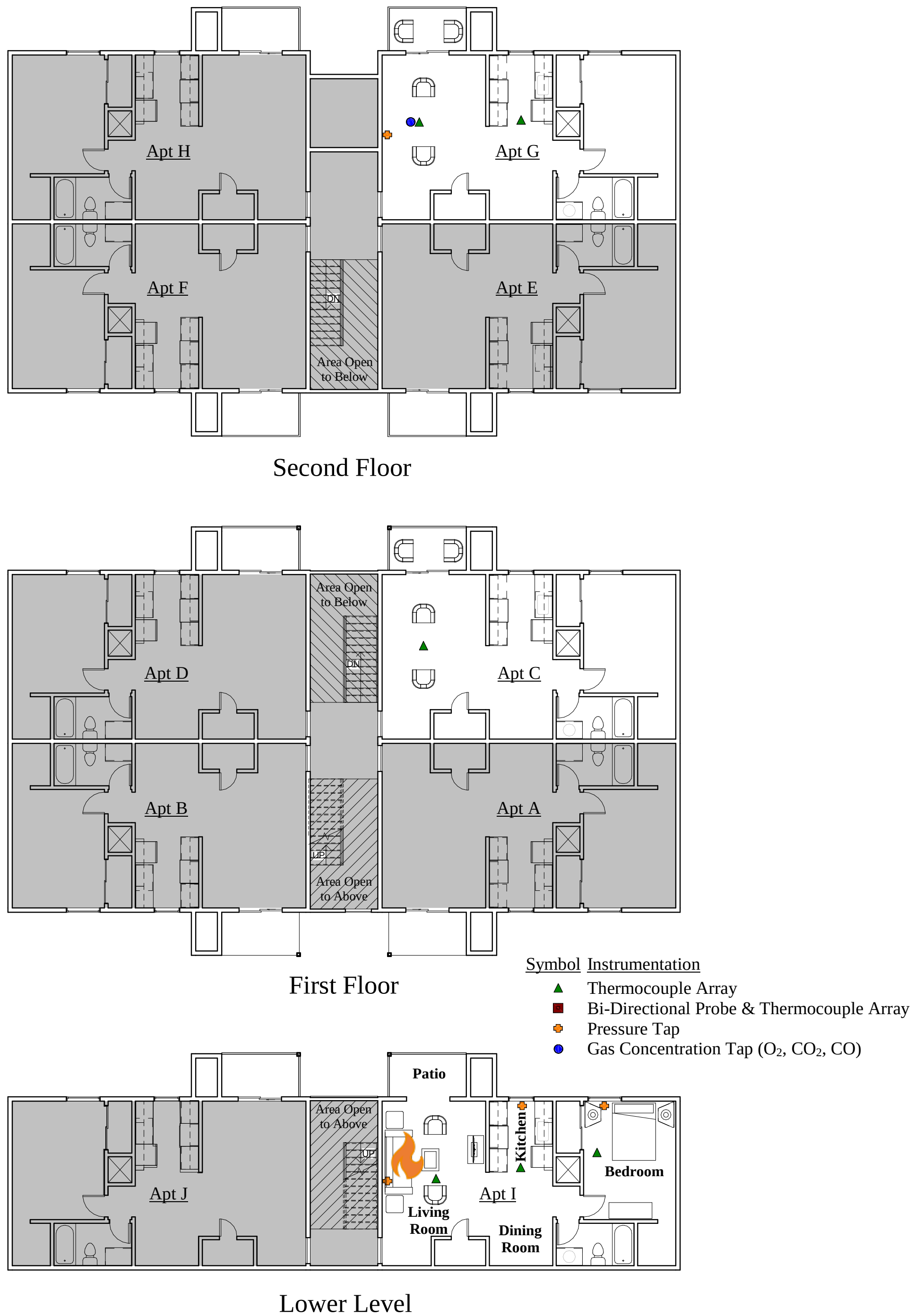


Figure 3.169: Instrumentation locations in Experiment 6.

The living room of Apartment I and kitchen of Apartments I, C, and G were furnished with the fuel loads described and photographed in Section 2.5. The living room fuel loads in Apartments C and G were each limited to only the two barrel chairs. In addition, two barrel chairs were placed on each of the balconies directly above the fire apartment (the Apartment C and G balconies) as fuel for exterior fire growth.

The fire in Experiment 5 was ignited with an electric match placed next to the arm of the sofa in the living room (t = 0 s) in Apartment I on the lower level. A smoke layer formed throughout the fire apartment, and smoke exhausted out of the open sliding glass door. The smoke layer descended to the floor by 308 s (5:08). At 461 s (7:41), the fire apartment kitchen window was broken by firefighters to provide additional ventilation to the fire. Within 10 s, flames began extending out of the sliding glass door, and within 54 s the living room transitioned to flashover as the fire grew in response to the additional ventilation. The fire continued to spread out of the fire apartment and up the side C exterior, igniting the first-floor balcony at 524 s (8:44), ingiting the second-floor balcony at 583 s (9:43), and eventually extending above the roof line. Figure 3.170 shows conditions on the side C exterior when the kitchen window was vented and immediately prior to exterior suppression.

(a) Vent Kitchen Window (461 s) (b) Prior to Exterior Suppression (656 s)

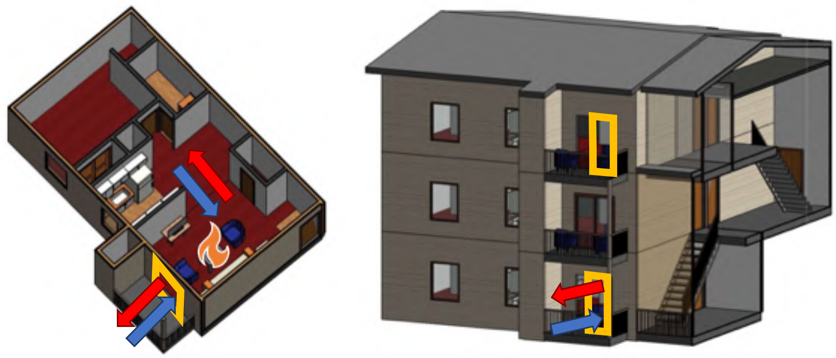
Figure 3.170: Images of the conditions on the side C exterior during firefighter interventions in Experiment 6.

The sliding glass door to Apartment G, two-floors directly above the fire apartment, was open throughout the experiment, allowing smoke to accumulate in that apartment as the fire grew. Flames began extending through the Apartment G sliding glass door by 600 s (10:00), shortly after the second-floor balcony ignited. The room then began to darken down as the smoke layer descended.

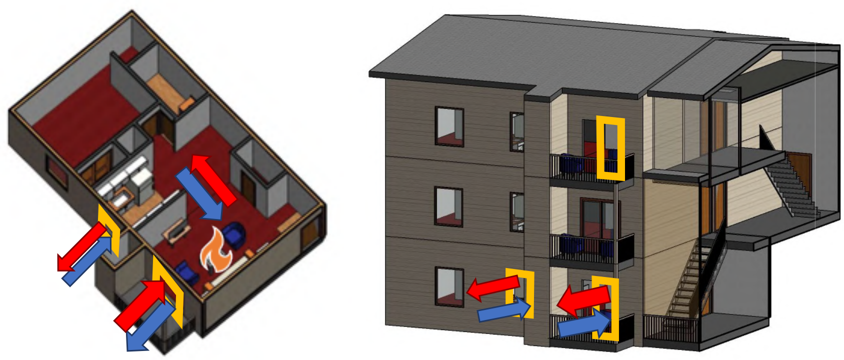
The sliding glass door to Apartment C, one-floor directly above the fire apartment, was closed at the start of the experiment. A curtain was hung on the inside of the apartment that covered half of the sliding glass door. Radiant heat from the fire spreading on the exterior caused the curtain to pyrolyze, and then ignite, by 645 s (10:45). At 653 s (10:53), 8 s later, the glass of the sliding glass door failed and the apartment filled with smoke and flames.

Firefighters began exterior fire control from side C at 656 s (10:56) using a combination nozzle set to a straight stream, attached to 200 ft of 1 3/4 in. hoseline, and flowing 150 gpm. The hose stream was directed through the fire apartment sliding glass door and at the balconies and eave line above. After 69 s of flowing water, the nozzle firefighter repositioned closer to the structure, then flowed water through the fire apartment sliding glass door for another 60 s. In total, 256 gallons of water was used during initial exterior fire control, which successfully knocked down the fire. Any water flow after 800 s (13:20) was utilized during overhaul operations.

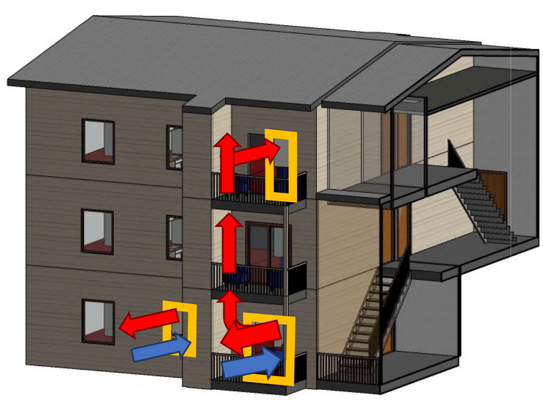
The flow of combustion gases and fresh air during Experiment 6 are sketched in Figure 3.171. As the fire grew in the living room of Apartment I, high-temperature, lower density fire gases rose and began to fill the fire compartment from the top down. The kitchen was open to the living room so the common space filled simultaneously. Once the hot gas layer reached the top of the open sliding glass door in the living room, gases began exhausting to the environment. Entrainment from the fire plume drew air through the lower portion of the sliding glass door into the fire compartment, which led to further fire growth (see Figure 3.171a). The kitchen window was then vented by firefighters, which provided a new exhaust for the higher pressure gases and air intake. The gases exhausted out of the top portion of the window while cooler, ambient air was entrained through the lower portion of the vent (see Figure 3.171b). The fire apartment then transitioned to flashover and the fire spread up the exterior of the building on side C, reaching Apartment G on the second floor. The sliding glass door to Apartment G was half open, which allowed smoke to accumulate and eventually flames to extend into the apartment (see Figure 3.171c). Shortly prior to suppression, the sliding glass door to the first-floor apartment (Apartment C) failed, allowing fire spread into that apartment (see Figure 3.171d). Exterior fire control knocked down the fire, which stopped the production of combustion gases.



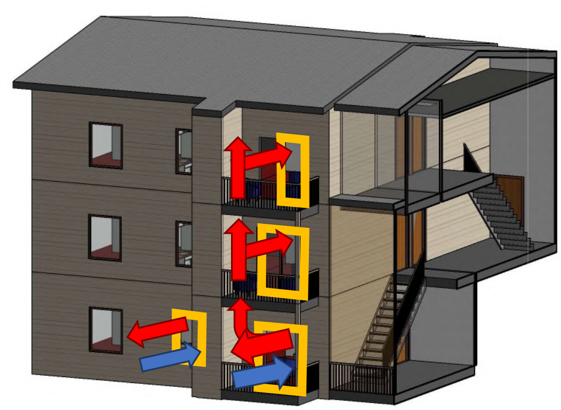
(a) Prior to Any Ventilation Changes



(b) After Kitchen Window Was Vented



(c) Exterior Fire Growth Reached the Second Floor



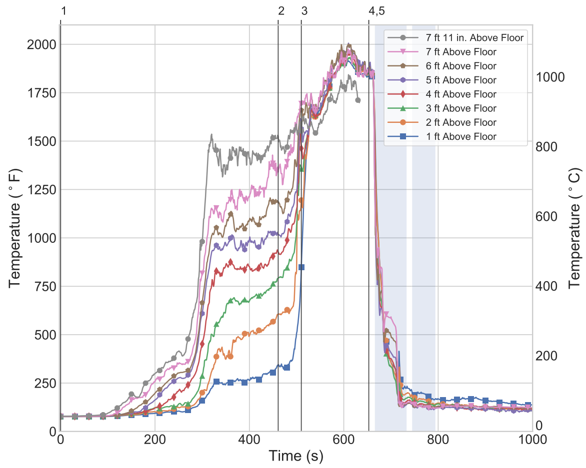
(d) After Apt. C Sliding Glass Door Failed

Figure 3.171: Changes in flow during Experiment 6. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

The time histories of the fire apartment temperatures are presented in Figure 3.172. The temperature near the living room ceiling began to increase by 90 s (1:30) post ignition. At 320 s (5:20), the fire reached a steady, ventilation-limited state, with living room temperatures ranging between 240 °F 1 ft above the floor to 1540 °F 1 in. below the ceiling. Conditions remained steady until the kitchen window was vented at 461 s (7:41). The additional ventilation provided oxygen to the fire, which resulted in an increase in heat release rate. Within 54 s of venting the kitchen window, at 515 s (8:35), the living room transitioned to flashover (i.e., temperatures at all elevations exceeded 1100 °F). The peak living room temperatures were between 1845 °F and 2010 °F at all elevations. The living room remained in a post-flashover state until the start of exterior fire control at 656 s (10:56), which reduced the living room temperatures.

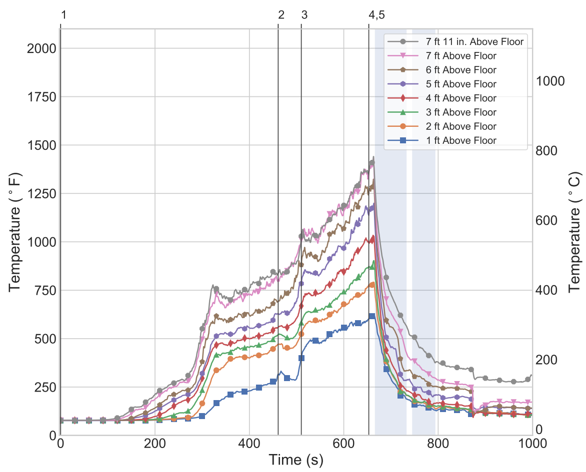
Temperatures in the kitchen of the fire apartment showed similar behavior to temperatures in the living room, but with lower peaks. Temperatures near the ceiling began to increase at 100 s (1:40). Temperature at all elevations were increasing through the ventilation of the kitchen window. After the kitchen window was vented at 461 s (7:41), temperatures below 6 ft temporarily dropped 10 °F to 50 °F as fresh air was entrained through the bottom of the window. Within 40 s of venting the window, however, temperatures at all elevations increased. Between 515 s (8:35), when the living room transitioned to flashover, and 656 s (10:56), when exterior fire control began, the range of temperatures in the kitchen increased from 440 °F to 1060 °F to 610 °F to 1400 °F. The kitchen temperatures decreased in response to the start of suppression.

Temperatures in the bedroom remained lower than in the kitchen or living room due to the closed bedroom door. Smoke leaking through the top of the bedroom door kept the temperature 1 in. below the ceiling higher than the temperatures at lower elevations. The temperatures at all elevations increased steadily until the start of suppression. The temperature 1 in. below the ceiling reached a peak of 340 °F, while the temperatures at lower elevations remained below 160 °F. The bedroom temperature then steadily declined after the start of exterior fire control due to knock down of the fire.

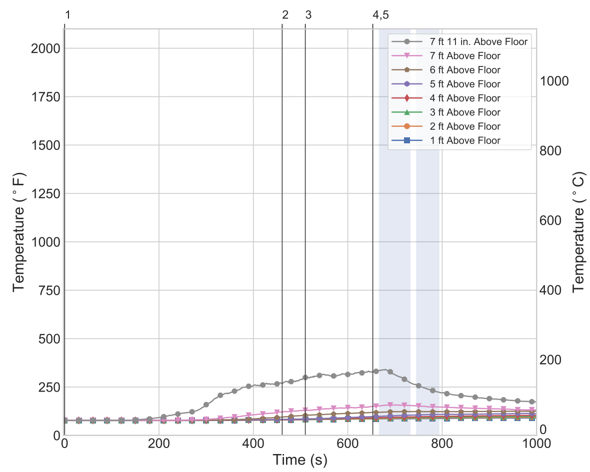


(a) Living Room

	Action/Event	Time (s)
1	Ignition	0
2	Vent kitchen window	461
3	Flashover in living room	515
4	Apartment C (first-floor) sliding door failed	653
5	Begin exterior water application from side C	656



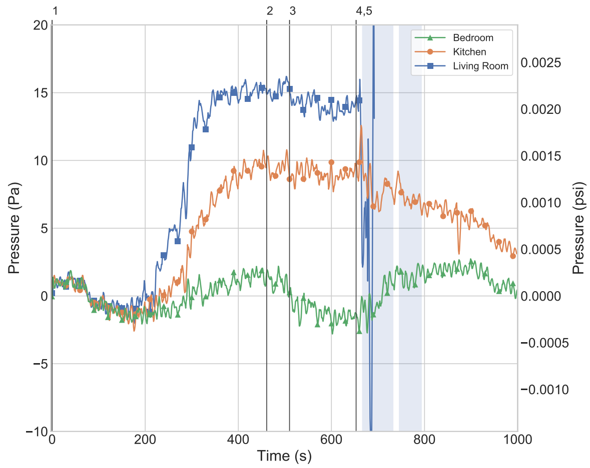
(b) Kitchen



(c) Bedroom

Figure 3.172: Fire apartment (Apartment I) temperatures for Experiment 6. Blue shaded regions indicate time and duration of water flow.

The pressure measurements in the fire apartment reflect the growth stages of the fire, with greater magnitudes in rooms closer to the fire origin (see Figure 3.173). The pressure in the bedroom remained near ambient conditions ±2 Pa throughout the entire experiment due to the closed bedroom door isolating the room from the fire. The pressure measurements in the living room and kitchen of the fire apartment began to increase at 200 s (3:20) as the smoke layer descended below the measurement height of 4 ft. The living room and kitchen pressures became steady by 340 s (5:40) with values of 15 Pa and 10 Pa, respectively. Despite venting the kitchen window and the living room transitioning to flashover, the pressures remained at approximately the same values until the start of suppression at 656 s (10:56). The pressures then decreased as the gases cooled and contracted due to suppression.

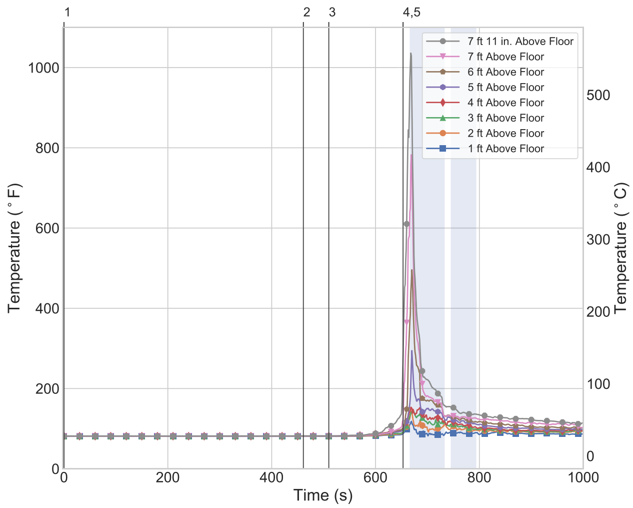


	Action/Event	Time (s)
1	Ignition	0
2	Vent kitchen window	461
3	Flashover in living room	515
4	Apartment C (first-floor) sliding door failed	653
5	Begin exterior water application from side C	656

(a) Fire Apartment (Apt. I)

Figure 3.173: Fire apartment pressures for Experiment 6. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

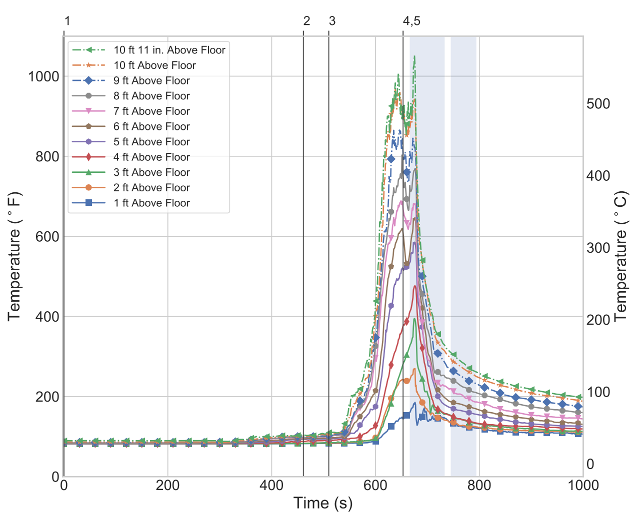
The temperature in the living room of the first-floor apartment directly above the fire apartment (Apartment C) remained ambient and steady (about 80 °F) until 610 s (10:10), at which point the Apartment C balcony was fully engulfed in fire (see Figure 3.174). Radiant heat from the fire spreading on the exterior impacted temperatures in the apartment and began to pyrolyze the curtains on the interior of the sliding glass door. The temperature 1 in. below the ceiling responded first and increased gradually. The curtains then ignited 645 s (10:45) post-ignition. At 653 s (10:53), both sections of the sliding glass door failed, which allowed flames to extend into the apartment. Temperatures increased, reaching peaks ranging from 120 °F 1 ft above the floor to 1035 °F 1 in. below the ceiling. It is important to note that the temperature array was centered in the living room and a barrel chair was between the array and sliding glass door, which was why temperatures measured 4 ft and below showed a muted response. Suppression began immediately after at 656 s (10:56), which quickly decreased temperatures to below 150 °F.



	Action/Event	Time (s)
1	Ignition	0
2	Vent kitchen window	461
3	Flashover in living room	515
4	Apartment C (first-floor) sliding door failed	653
5	Begin exterior water application from side C	656

Figure 3.174: Living room temperatures in the first-floor apartment directly above the fire apartment (Apartment C) for Experiment 6. Blue shaded regions indicate time and duration of water flow.

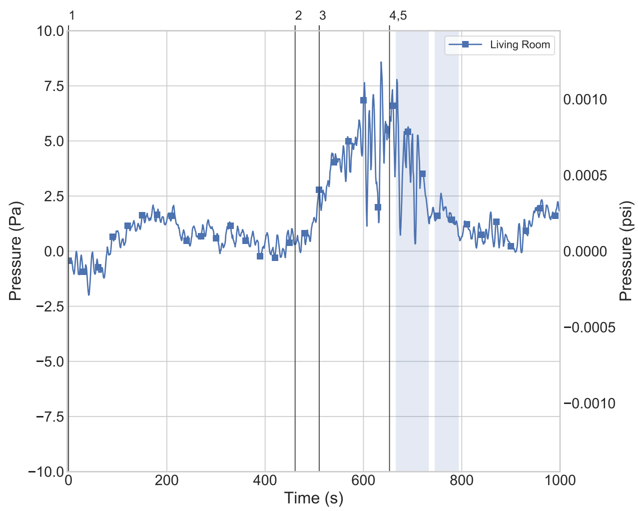
In Apartment G, two-floors directly above the fire apartment, the living room temperatures first began to increase at 535 s (8:55), as smoke moved through the open sliding glass door (see Figure 3.175). Flames began extending into Apartment G from the exterior by 600 s (10:00), increasing temperatures at all elevations. The temperatures continued increasing until the start of suppression, reaching peaks ranging between 145 °F 1 ft above the floor and 1005 °F 1 in. below the ceiling. Temperatures at all elevations then quickly decreased in response to suppression.



	Action/Event	Time (s)
1	Ignition	0
2	Vent kitchen window	461
3	Flashover in living room	515
4	Apartment C (first-floor) sliding door failed	653
5	Begin exterior water application from side C	656

Figure 3.175: Living room temperatures in the second-floor apartment directly above the fire apartment (Apartment G) for Experiment 6. Blue shaded regions indicate time and duration of water flow.

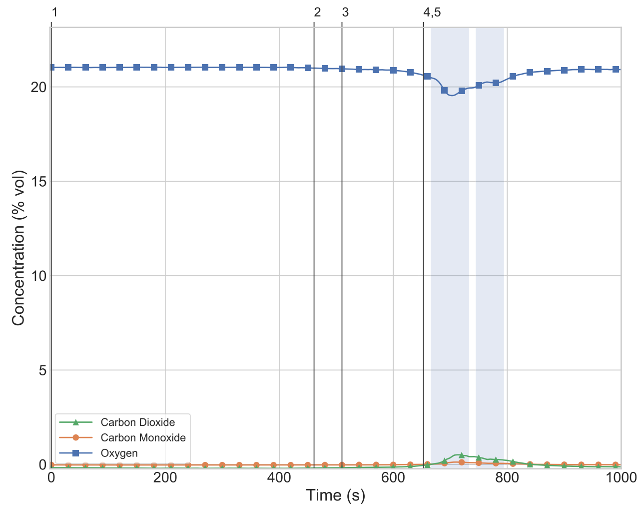
Pressure was also measured in the living room of the second-floor apartment directly above the fire apartment (Apartment G, see Figure 3.176). The pressure remained ambient and steady until the fire apartment kitchen window was vented at 461 s (7:41), which allowed rapid fire growth. The high-velocity gases on the exterior of the structure began to enter Apartment G through the open sliding glass door and accumulate, filling from the top down. As the gases and subsequent fire flowed into the apartment, the pressure began to increase steadily, reaching a maximum of 9 Pa by 656 s (10:56). At that time, exterior suppression began, which knocked down the fire, allowing the pressure in Apartment G to equalize with the exterior and return to ambient conditions.



	Action/Event	Time (s)
1	Ignition	0
2	Vent kitchen window	461
3	Flashover in living room	515
4	Apartment C (first-floor) sliding door failed	653
5	Begin exterior water application from side C	656

Figure 3.176: Pressures in the second-floor apartment (Apartment G) living room for Experiment 6. Each pressure tap was installed 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

Gas concentrations were measured in the living room of Apartment G (Figure 3.177). Gas concentrations began to change prior the start of exterior fire control at 630 s (10:30) The impact on gas concentrations was limited: Apartment G gas concentrations reached peaks of 19.5% O_2, 0.2% CO (2000 ppm), and 0.6% CO_2 before returning to ambient conditions, beginning 46 s after the start of exterior suppression.



	Action/Event	Time (s)
1	Ignition	0
2	Vent kitchen window	461
3	Flashover in living room	515
4	Apartment C (first-floor) sliding door failed	653
5	Begin exterior water application from side C	656

Figure 3.177: Second-floor apartment (Apartment G) living room gas concentrations for Experiment 6. Measurement location was 4 ft above the floor. Blue shaded regions indicate time and duration of water flow.

4 Discussion

In this section, the changes in fire dynamics as a function of varying initial conditions (e.g., fire location and vent openings) and varying suppression and ventilation tactics are analyzed with respect to the impact on estimated occupant tenability in the fire apartments and egress stairwell. Experiments are analyzed based on the scenarios examined as well as across scenarios to provide quantification to the experimental variables studied.

4.1 Estimated Occupant Gas Exposure

The potential inhalation exposure hazard to occupants considers a subset of the products of combustion. This was estimated by computing the fractional effective dose (FED) from gas concentration measurements obtained in the fire apartment and common stairwell to generate a time-dependent exposure of a potential occupant to toxic gases. Tenability analyses are typically incorporated into building design to estimate the time at which an occupant would no longer be able to affect their own egress from a fire of a given size. In practice, however, even occupants who have met or exceeded the criteria for incapacitation may be able to survive their exposures if rapidly located, removed, and provided appropriate medical attention. For this reason, FED values can be used to assess the effects of firefighting interventions, but should not necessarily be employed as a predictor of lethality.

FED can be used to describe the percentage of the population for which conditions become untenable. Although a detailed description of the mathematical relationship is beyond the scope of this report, FED is related to the probability of the conditions being non-tenable for a certain percentage of the population through a lognormal distribution. For example, an FED of 0.3 is the criterion used to determine incapacitation for susceptible individuals (i.e., young children, elderly, and/or unhealthy occupants) and corresponds to untenability for 11% of the population. An FED of 1.0 is the value at which 50% of the population would experience untenable conditions, and an FED of 3.0 is the value at which 89% of the population would experience untenable conditions. The FED equation for toxic exposure can include a number of products of combustion, but these experiments focused on the most common gases produced at high concentrations during residential structure fires. In this case, the general N-gas equation can be simplified to include the following [31]:

$$FED_{toxic} = (FED_{CO} * HV_{CO_2}) + FED_{O_2} \tag{4.1}$$

In Equation 4.1, FED_{CO} and FED_{O_2} are the doses of carbon monoxide inhalation (CO) and low oxygen (O_2) resulting in hypoxia, respectively, and HV_{CO_2} is the hyperventilation factor due to CO_2 inhalation, each a function of time. The expression for FED_{CO} is shown in Equation 4.2:

$$FED_{CO}(t) = \int_0^t 3.317 * 10^{-5} [\phi_{CO}]^{1.036} (V/D) dt \tag{4.2}$$

where ϕ is the CO concentration in parts per million, dt is the time step, V is the volume of air breathed each minute in liters, and D is the exposure dose in percent carboxyhemoglobin (% COHb) required for incapacitation.

Values of V and D vary depending on the level of work being conducted by the subject. The default case is often taken to be light work (e.g., crawling to evacuate a structure), which corresponds to D = 30% COHb and V = 25 L/min. The uptake rate of CO and other products of combustion can vary considerably with V, and is dependent on a number of factors, including hyperventilation induced by exposure to CO_2. This increase in respiration rate due to CO_2 inhalation is accounted for in Equation 4.1 by the hyperventilation factor. This factor, HV_{CO_2}, is defined in Equation 4.3:

$$HV_{CO_2}(t) = exp\left(\frac{0.1903(exp(\phi_{CO_2})) + 2.0004}{7.1}\right) \tag{4.3}$$

where ϕ_{CO_2} is the mole fraction of CO_2. Lastly, the fraction of an incapacitating dose due to low oxygen hypoxia, FED_{O_2} , is calculated by:

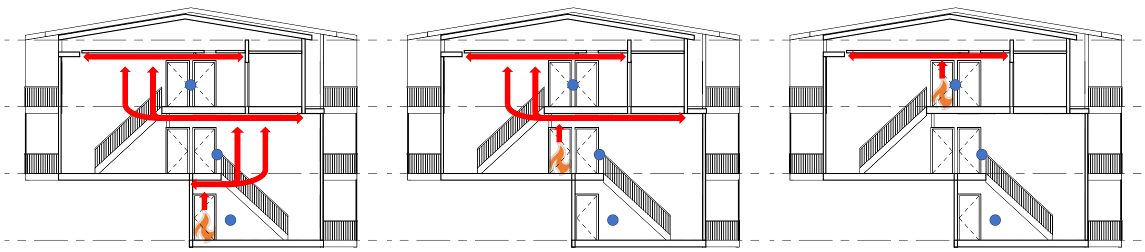
$$FED_{O_2}(t) = \int_0^t \frac{dt}{exp[8.13 - 0.54(20.9 - C_{O_2}(t))]} \tag{4.4}$$

where dt is the time step and C_{O_2} is the O_2 concentration (volume percent).

Again, it is important to note that the threshold criteria for untenability (FED = 0.3, FED = 1.0, and FED = 3.0) predict the onset of incapacitation, not lethality. CO intoxication is driven primarily by the carboxyhemoglobin concentration in the bloodstream. Hemoglobin has a higher affinity for carbon monoxide than oxygen, so high COHb levels have an asphyxiating effect on the body. Based on work published by Purser in *Fire Toxicity*, incapacitating levels of COHb in the bloodstream range between 30% and 40% for the majority of the population, although susceptible populations may experience loss of consciousness at levels as low as 5% [32]. It is important to recognize that incapacitating levels of COHb have been found in surviving fire victims [31]. Active subjects are typically more severely affected by COHb concentrations than sleeping subjects. Lastly, median COHb levels of 50% are considered to be the threshold for lethality [32].

As gas concentrations and the resultant FEDs can vary considerably prior to fire department intervention, due to differences in initial fire growth, it can also be useful to consider the rate of change of the FED, or the fractional effective rate (FER). The FER can be used to assess the rate at which the exposure to a potential occupant would be increasing or decreasing. The FED itself can only increase or remain stagnant—it can never decrease—but a decreasing FER would indicate that an intervention is improving conditions.

The enclosed common stairwell provided a distinct path for smoke movement that facilitated smoke to fill from the upper floors down versus accumulation on a lower floor first. For example, if smoke originated from a lower-level fire apartment, it traveled laterally across the bottom of the first-floor landing, and through buoyancy, would rise to the next floor. Gases would then flow along the bottom of second-floor landing. With the front half of the landing open to the second floor, gases would continue to rise, spilling into the second floor before accumulation would begin from the ceiling of the landing. The flow of gases for fires that originated on any of the three levels are show in Figure 4.1.



(a) Lower-Level Fires (b) First-Floor Fires (c) Second-Floor Fires

Figure 4.1: Smoke travel within the stairwell during lower-level, first-floor, and second-floor fires. The blue circles represent the locations of gas concentrations measurements.

The flow of gases combined with the single-point measurements of gas concentrations limit some of the conclusions that can be drawn regarding occupant tenability. The single point measurement locations within the stairwell can present an incomplete overview of smoke flow if provided without context from the other stairwell instrumentation. Gas concentration instrumentation was located 4 ft above the floor and responded once the smoke layer descended past or flowed past this elevation. Therefore, it is possible there were locations within the stairwell on the same floor as the measurement locations where gas concentrations and resulting FED could have been better or worse for potential occupants. The stairwell layout and large volume also created a time delay between when smoke was first apparent on the floor due to smoke movement, and when the change in gas concentrations was recorded due to smoke filling.

There were also gas concentration measurement limitations within the fire apartment. Although the apartments were identical in layout, the apartments located on the second floor had peaked living room ceilings, with a height of 11 ft, 2 in. at the peak and 9 ft, 5 in. at the edge. The lower-level and first-floor living room ceilings were 8 ft in height. This additional height limited the ability of direct comparisons between some experiments. Lastly, during Experiment 3A, the fire extended into the attic due to a failed ceiling which provided additional volume for smoke accumulation. This caused the smoke layer to remain above the gas concentration instrumentation and resulted in no measured change in gas concentration within the fire apartment, although smoke was present within the compartment.

4.2 Estimated Firefighter Thermal Exposure

In 1973, Utech suggested a combination of the local air temperature and the incident heat flux to estimate the components of radiative and convective heat transfer, respectively, to a firefighter. He used these two quantities to define three ranges of firefighters' operational thermal conditions: routine, ordinary, and emergency [33]. According to Utech, routine conditions are those with a surrounding temperature between 70 °F (20 °C) and 162 °F (72 °C) and an incident heat flux between 1 kW/m^2 and 2 kW/m^2. Utech maintained that these conditions translate approximately to ambient environments such as those experienced outside a typical structure fire to those that may be present during the overhaul phase of a fire. The thermal environment crosses into the ordinary operating range when temperatures were between 162 °F (72 °C) and 572 °F (300 °C) and heat fluxes between 2 kW/m^2 and 12 kW/m^2. Ordinary operating conditions include thermal environments that might be encountered next to a post-flashover room. According to Utech, firefighters are likely able to function under ordinary operating conditions from 10 min. to 20 min. at a time, or for the approximate working duration of an SCBA cylinder. Utech suggested that ordinary operating conditions were those typical of a house fire. Emergency operating conditions are present when heat flux exceeds 12 kW/m^2 and temperature is in excess of 572 °F (300 °C). These conditions resulted in increased risk for injury to a firefighter even when operating in PPE. Utech describes the emergency zone as one in which a PPE of a firefighter is only able to withstand an exposure on the order of a few seconds. The thresholds for the thermal operating classes are illustrated in Figure 4.2.

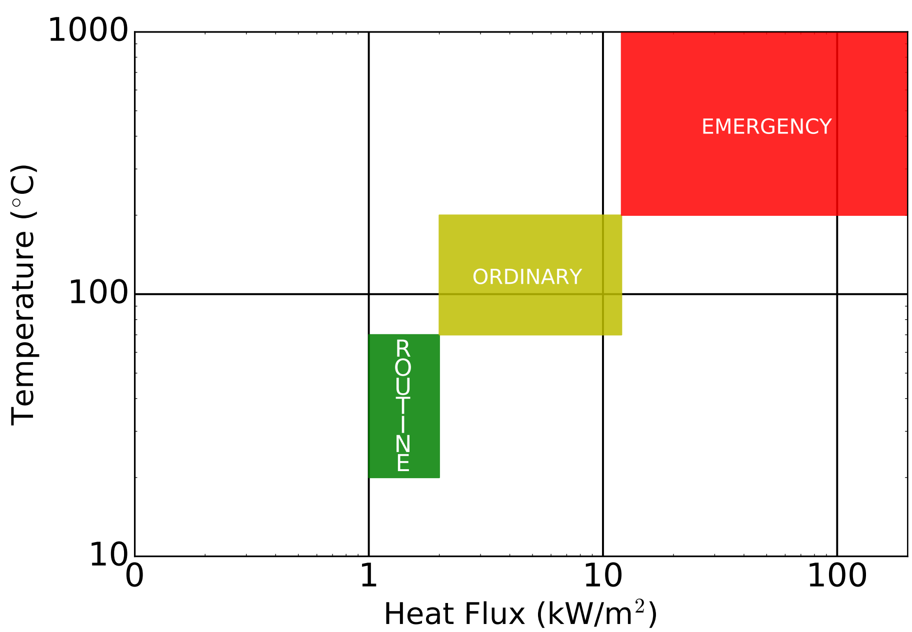


Figure 4.2: Thermal Operating Classes

It is important that Utech's definition of the ordinary operating class is understood in the proper context. It is likely that a typical fire in the 1970's, when the thermal classes were developed, may be different than a fire with mostly synthetic fuels as is common almost 50 years later. The state of the art in personal protective equipment has advanced considerably since the 1970s, as has the battery of performance standards for firefighter PPE [34, 35].

Madrzykowski [36] compiled previous research efforts to characterize the thermal operating environment of firefighters. The literature review highlighted that evaluating the operating environment of firefighters by pairing temperature and heat flux may not appropriately reflect the entire range of conditions encountered by firefighters. Additionally, the thermal conditions within a structure can rapidly change from environments where firefighters would be safe to conditions where firefighters would be in immediate danger. More sophisticated characterization of heat transfer through firefighter turnout gear and appropriate exposure thresholds for firefighter turnout gear are an area of ongoing research.

Heat flux measurements were not made as part of this experimental series. As a result, discussion of potential firefighter exposure thresholds should be considered to be conservative. Data for only part of the Utech thermal operating classes was measured and based on work from Madrzykowski [36], those classes can be considered to be an incomplete representation of firefighter exposure.

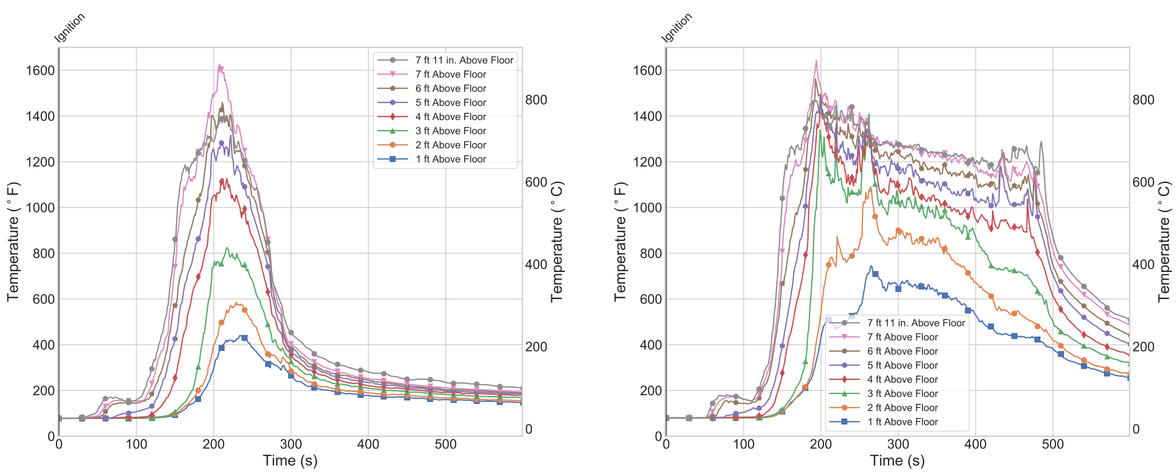
4.3 Fire Growth Prior to Firefighter Intervention

Initial fire growth is one metric that can be used to quantify the differences between the experimental scenarios, and ultimately the individual experiments. Initial fire growth is characterized as the period of time between ignition and the first firefighter intervention. Examination of this time period provides insight into the impact of changes in static variables such as ventilation openings, fire locations, and experimental volumes. The following sections examine Scenarios 1–3 because the fire location and interior and exterior vents varied prior to ignition.

4.3.1 Lower-Level Bedroom Fire – No Fire Showing

Experiments 1A and 1B were designed to evaluate the effect of different experimental volumes on the behavior of a lower-level bedroom fire with no exterior ventilation prior to firefighter intervention. Experiment 1A incorporated only the volume of the fire apartment during initial growth. During Experiment 1B, the fire apartment door was open from ignition. Therefore, the experimental volume included both the apartment and the enclosed stairwell.

In Experiments 1A and 1B, the fire room temperatures began to rise between 30 s and 40 s following ignition, as shown in Figure 4.3. The ceiling temperatures reached initial peaks of approximately 1630 °F 206 s post-ignition for Experiment 1A, and 1640 °F 195 s post-ignition for Experiment 1B. Temperatures 1 ft above the floor in Experiment 1A peaked at 440 °F 230 s post-ignition compared to Experiment 1B, where 1 ft above the floor temperatures peaked at 750 °F 265 s post ignition. The higher peak floor temperatures and longer duration of sustained elevated temperatures during Experiment 1B was indicative of the additional oxygen available for combustion due to the open apartment door. The open door in Experiment B allowed the combustion gases to exhaust out of the fire apartment and, through buoyancy, fill the stairwell from the top down. This excess volume prolonged the layer descent in the fire apartment and also allowed for air from the stairwell to be entrained into the fire apartment.



(a) Experiment 1A

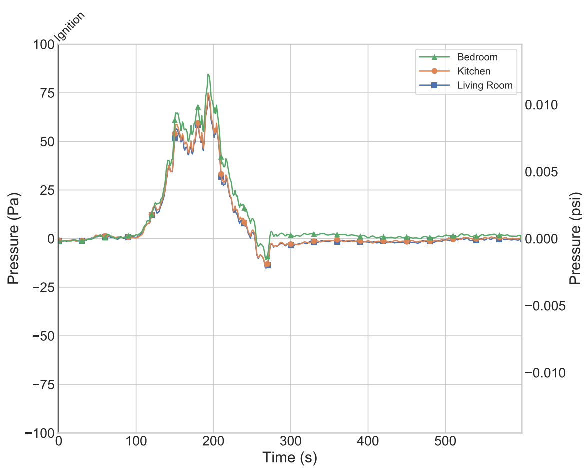
(b) Experiment 1B

Figure 4.3: Fire room (bedroom) temperatures from ignition to firefighter intervention in Experiments 1A and 1B.

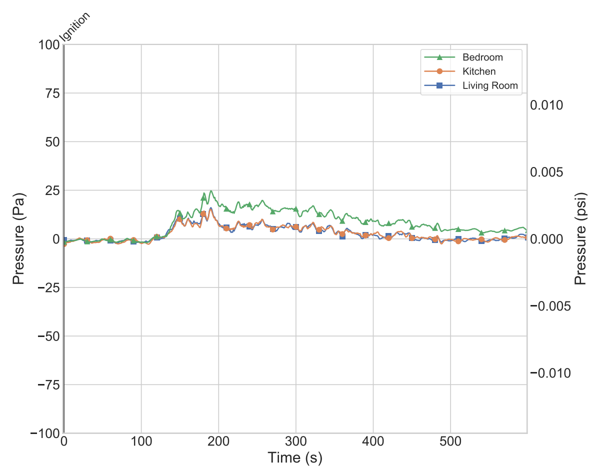
Although peak fire room temperatures in both experiments suggest a ventilation-limited state was reached in approximately 200 s, the additional volume of fresh air provided by the stairwell allowed the bedroom fire in Experiment 1B to sustain combustion for a longer than Experiment 1A. The volume in the stairwell above the fire apartment led to a slower descent rate of the smoke layer in the fire apartment (smoke flowed into stairwell and filled from the top down), and therefore longer duration of entrainment of air entrainment from the stairwell. Had the fire apartment been on a higher floor, the volume above would have been decreased and therefore the smoke layer would have descended faster. As a result, there would have been less air entrainment.

Fire room ceiling temperatures in Experiment 1B remained above 1100 °F for approximately 339 s, while fire room ceiling temperatures in Experiment 1A remained above 1100 °F for approximately 110 s, a much shorter duration. At oxygen levels between 13%–15%, flaming combustion is difficult to sustain [29], so combustion continued to occur in Experiment 1B until approximately 485 s as oxygen concentrations in the living room remained between 17%–18%. Note: The living room was likely to have higher concentrations than the fire room due to proximity to the fire. The sharper decline in temperature in Experiment 1A is related to the oxygen concentration in the living room dropping below 15% at 206 s, ultimately reaching a minimum of 10%.

As the fire room temperatures increased, pressures in the fire apartment also increased for both Experiments 1A and 1B as presented in Figure 4.4. Initial pressures peaked throughout the apartment between approximately 73 Pa and 85 Pa from 191 s to 193 s in Experiment 1A. In Experiment 1B, the open apartment door limited the initial pressure peak to approximately 15 Pa to 25 Pa. As Experiment 1A progressed, the sharp pressure drop coincided with the drop in temperature as the fire self-extinguished due to a lack of oxygen available for combustion and gases contracted. Gas contraction resulted in minimum pressure between approximately -11 Pa to -15 Pa at 266 s. In Experiment 1B, fire apartment pressures decreased gradually, similar to the temperatures. Pressures remained above ambient until 480 s post-ignition, corresponding to the change in temperature decay rate. The apartment pressures did not become negative in Experiment 1B because the experimental volume was larger, combustion was sustained longer, and temperatures returned to ambient more gradually.



(a) Experiment 1A



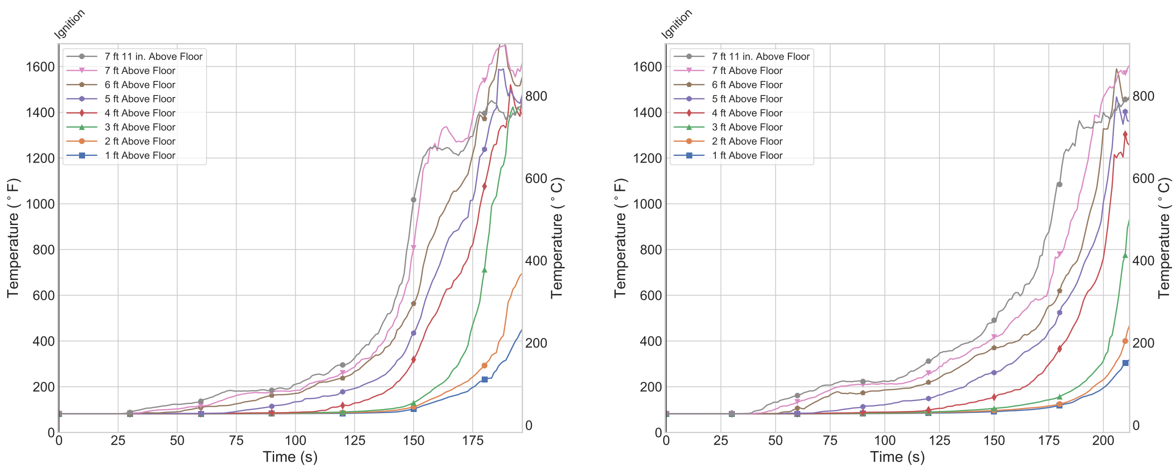
(b) Experiment 1B

Figure 4.4: Fire apartment pressures from ignition to firefighter intervention in Experiments 1A and 1B.

4.3.2 First-Floor Bedroom Fire – No Fire Showing

Experiments 1C and 1D were designed to evaluate the effect of horizontal ventilation ahead of interior suppression for a first-floor bedroom fire. Firefighter intervention in these two experiments, which was performed earlier than in Experiments 1A and 1B, was timed to coincide with the development of ventilation-limited conditions in the fire apartment. In both Experiments 1C and 1D, there were no ventilation openings, either interior or exterior, present prior to ignition. Experiment 1D included door control of the fire apartment door during suppression, and, after the initial knock down, hydraulic ventilation.

In Experiment 1C, fire room ceiling temperatures peaked to approximately 1650 °F at 188 s post ignition (see Figure 4.5), and by 195 s oxygen concentrations dropped below 15%. This level of oxygen concentration would suggest that fire growth was likely impacted by the amount of oxygen available for combustion. The first firefighter intervention occurred at 197 s while ceiling temperatures remained above 1250 °F. In Experiment 1D, fire room ceiling temperatures peaked at approximately 1625 °F 213 s post ignition, coinciding with firefighter intervention.



(a) Experiment 1C

(b) Experiment 1D

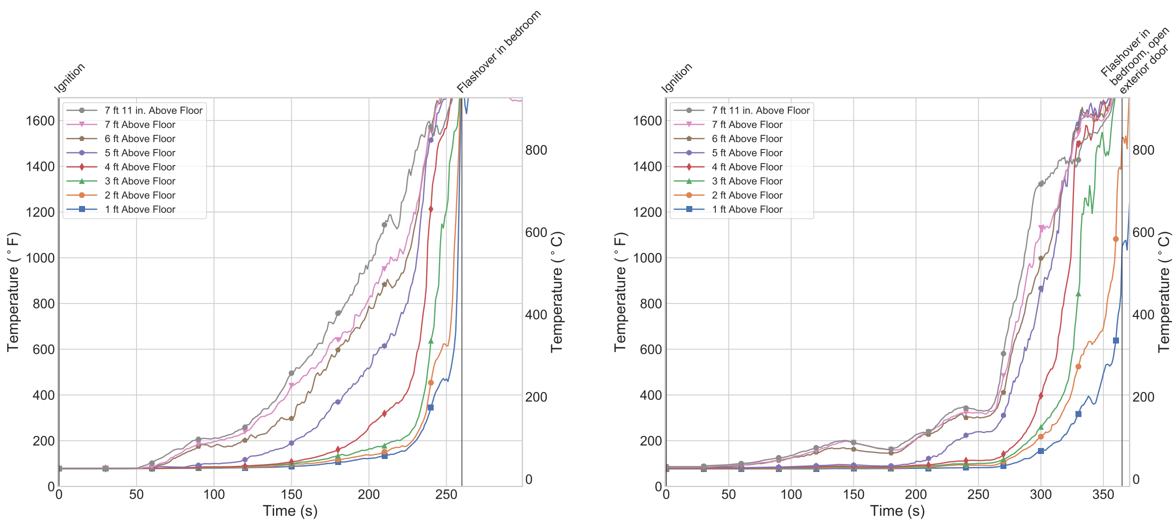
Figure 4.5: Fire room (bedroom) temperatures from ignition to firefighter intervention in Experiments 1C and 1D.

The fire growth in the first 200 s after ignition was comparable for the three bedroom fire experiments with no exterior ventilation (Experiments 1A, 1C, and 1D). Fire room ceiling temperatures peaked to an average of 1625 ±13 °F approximately 210 ± 21 s post ignition. After reaching the peak, temperatures, pressures, and oxygen concentrations began to decrease, indicating the fires were transitioning to a ventilation-limited state. At the time of this peak, the temperatures close to the floor were below the threshold for flashover (approximately 1100 °F), indicating the volume of air in the apartment alone was insufficient to allow sustained fire growth for flashover. Experiment 1B, which had a larger experimental volume due to the open apartment door to the common stairwell, reached a similar peak temperature—1635 °F at 193 s after ignition—but did not immediately begin to decay similar Experiments 1A, 1C, and 1D. Although the experimental volume in Experiment 1B included additional oxygen, the oxygen in the stairwell was not transported to the fire room in an efficient enough manner to support a transition to flashover. Rather, the fire in Experiment 1B maintained a fully developed state until approximately 485 s after ignition, at which point it began to decay due to a lack of oxygen available for combustion.

4.3.3 First-Floor Bedroom Fire – Fire Showing

Experiments 2A and 2B were designed to compare PPV and PPA. Unlike the experiments in Scenario 1, the bedroom (fire room) window was open prior to ignition. This ventilation source allowed for sufficient exchange of combustion gases and air to support flashover of the bedroom fire prior to any firefighter intervention in both experiments. It is important to note that the fuel loading differed between these two experiments. Experiment 2A utilized the standard bedroom fuel load, and Experiment 2B utilized a fuel load comprised of living room furnishings.

Both experiments showed temperature rise at the ceiling level approximately 50 s post ignition. In Experiment 2A (with the bedroom furnishings), temperatures above 4 ft steadily rose to their peak as the room transitioned to flashover at 260 s. Temperatures near the floor in Experiment 2A were slower to respond: Temperatures below 4 ft first began to rise at approximately 150 s, and rose close to 1000 °F 30 s prior to flashover. Peak fire room temperatures of approximately 2000 °F occurred 270 s post-ignition (see Figure 4.6a). In Experiment 2B (with the living room furnishings), temperatures throughout the fire room were slower to rise. In addition to the different fuel loads, the experiments utilized different ignition sources: the bedroom set was started using the waste container package, while the sofa was lit directly via an electric match. For reference, at the time of flashover in Experiment 2A, temperatures in the fire room in Experiment 2B were still below 500 °F. Although Experiment 2B took longer to flashover (365 s versus 260 s) fire room temperatures in both experiments were approximately 1800 °F at firefighter intervention (see Figure 4.6b). This is an indication that despite differences in fuel load and ignition, there was sufficient fuel in both experiments, and the presence of the open fire room window was the critical driver for conditions at firefighter intervention compared to Scenario 1 experiments.



(a) Experiment 2A

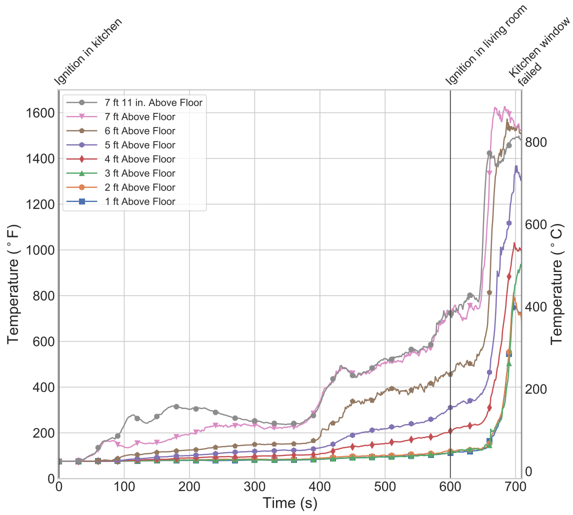
(b) Experiment 2B

Figure 4.6: Temperatures in the fire room (bedroom) for Experiments 2A and 2B prior to firefighter intervention.

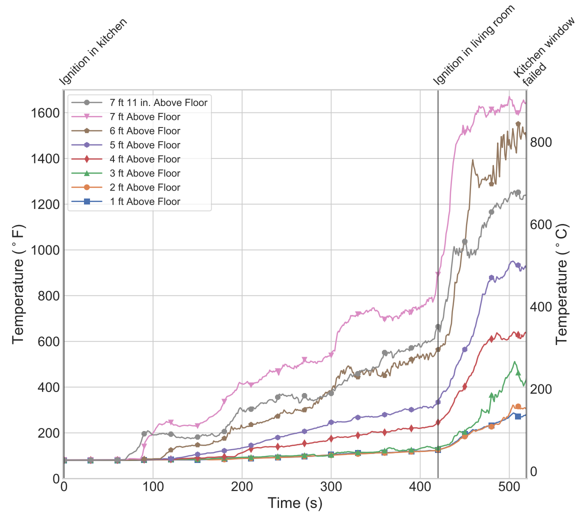
4.3.4 First-Floor Kitchen and Living Room Fire – Fire Showing

Experiments 3A and 3B were designed to assess interior suppression and exterior fire control for a first-floor kitchen fire that grew to living room involvement prior to firefighter intervention. In both experiments, the ignition location was in the kitchen with initial ventilation of the living room sliding glass door to half open. This ventilation established a flow path through the living room and around the wall shared by the kitchen and living room to the seat of the fire. This initial ventilation configuration was intended to help facilitate fire spread to the living room furniture from the kitchen fire. However, fire spread to the living room furnishings was not achieved in either experiment, and a secondary ignition was initiated via an electric match located on the corner of the living room sofa, furthest from the open sliding glass door. The kitchen fire growth was initially slower than the bedroom fire growth (in Scenarios 1 and 2) because of the arrangement of the fuel and that the fuel material supported slower flame spread.

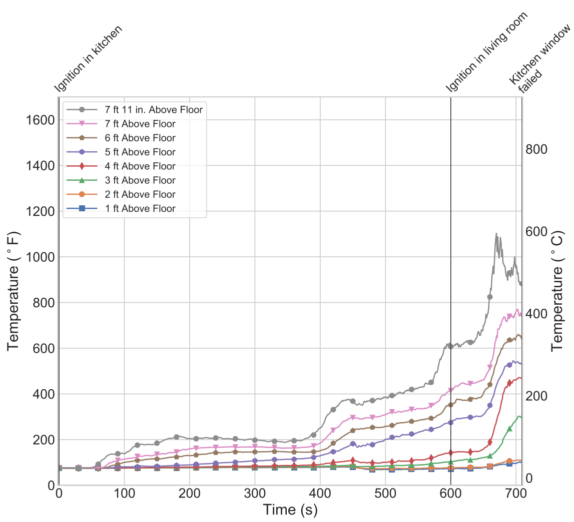
As ceiling temperatures in the kitchen crossed 800 °F, the living room ignition source was initiated (see Figure 4.7). Although the time to this threshold differed in the two experiments because of the natural variability in how the fires spread through the kitchen cabinets, the living room conditions in both experiments were similar (i.e., ceiling temperatures at 600 °F). Irrespective of the living room ignition, in both experiments the fires continued to grow in the kitchen, and kitchen ceiling temperatures (7 ft and above) rose to approximately 1500 °F, as the kitchen became fully-involved. Within 60 s of this temperature rise, the kitchen windows failed in each experiment. At the same time, living room temperature profiles showed a change in rate of temperature rise as the fire spread along the ignition sofa in the living room.



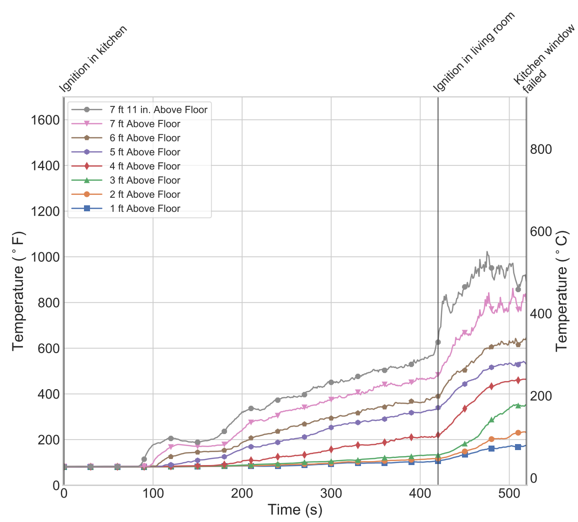
(a) Experiment 3A Kitchen



(b) Experiment 3B Kitchen



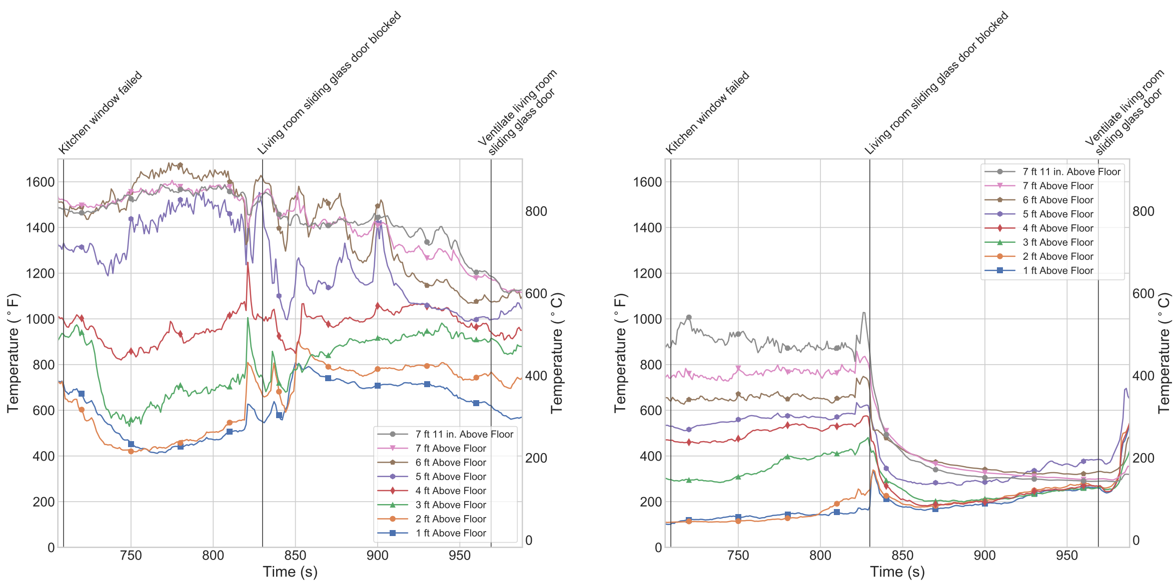
(c) Experiment 3A Living Room



(d) Experiment 3B Living Room

Figure 4.7: Kitchen and living room temperatures for Experiment 3A and 3B from ignition to the failure of the kitchen window.

Following the kitchen window failure in Experiment 3A, temperatures in the kitchen remained elevated and stratified, ranging from 400 °F 1 ft above the floor to 1600 °F at the ceiling (see Figure 4.8a. In the 100 s following the kitchen window failure, the living room temperature also remained nominally steady between 100 °F 1 ft above the floor to 1000 °F at the ceiling (see Figure 4.8b). At 808 s after ignition (100 s after kitchen window failure), the living room temperatures began to increase—rising between 30 to 40 °F in 20 s—before a piece of drywall fell from the ceiling and ended up blocking the lower portion of the sliding glass door. The drywall failure opened additional volume for smoke accumulation in the living room, which limited heat feedback to the fuel in the living room. The blockage of the sliding glass door also changed the air intake in the living room. Limiting the air entrainment into the living room slowed fire growth and ultimately dropped living room temperatures, as shown in Figure 4.8b. Temperatures began to recover approximately 150 s after the ceiling drywall failure, once firefighters completed venting the living room sliding glass door.

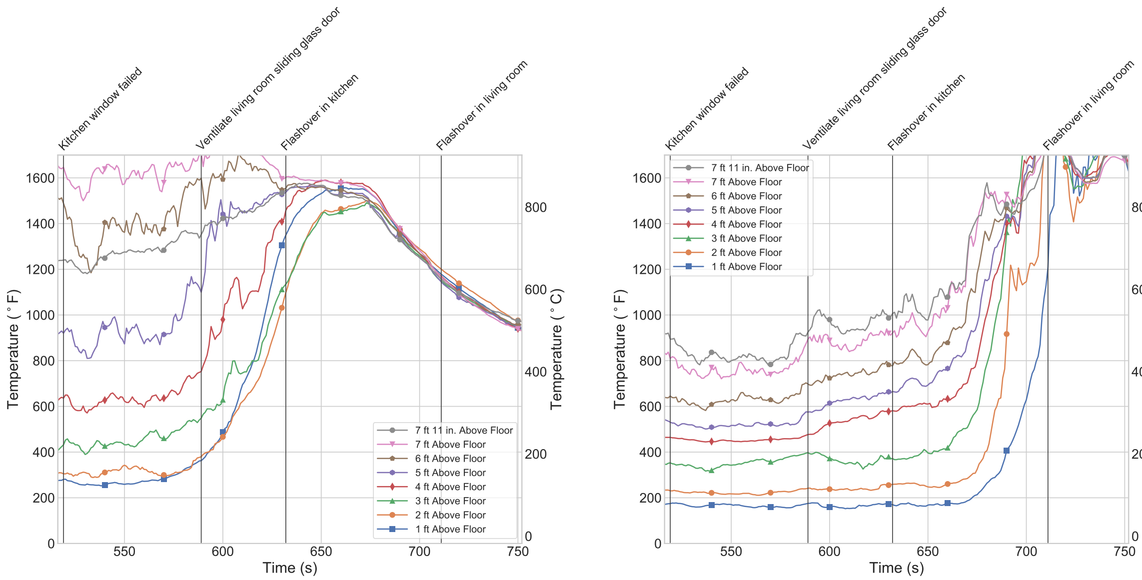


(a) Exp 3A Kitchen Temperatures

(b) Exp 3A Living Room Temperatures

Figure 4.8: Kitchen and living room temperatures post kitchen window failure for Experiment 3A.

The kitchen and living room temperatures in Experiment 3B post kitchen window failure were similar to Experiment 3A. Temperatures in the kitchen ranged from 250 °F 1 ft above the floor to 1600 °F at the ceiling (see Figure 4.9a), and temperatures in the living room ranged from 180 °F 1 ft above the floor to 900 °F at the ceiling (see Figure 4.9b). In Experiment 3B, the ceiling drywall did not fail and block air intake in the living room, instead, firefighters vented the second half of the living room sliding glass door. Following the additional ventilation, there was sufficient intake and exhaust through the fire apartment for both the kitchen and living room to transition to flashover.



(a) Exp 3B Kitchen Temperatures

(b) Exp 3B Living Room Temperatures

Figure 4.9: Kitchen and living room temperatures for Experiment 3B after the kitchen window failure.

In both experiments, the open living room sliding glass door that was present from the ignition of each fuel package provided sufficient ventilation to support fire growth in the kitchen until thermal conditions led to the window failure. This self-ventilation sustained the kitchen fire, with temperatures at the ceiling reaching above 1600 °F. The failure of the living room drywall in Experiment 3A, limited the repeatability of the living room fire development. In Experiment 3A the obstruction of the bottom portion of the living room sliding glass door impacted air intake in the living room, which subsequently limited fire growth. The blockage led to lower living temperatures compared to Experiment 3B. In both experiments, expanding the size of the vent in the living room (i.e., opening both panes of the sliding glass door) increased the oxygen available for combustion and led to temperature rises.

4.4 Horizontal Ventilation of a Bedroom Fire with No Fire Showing

Previous research emphasized that when air was introduced to an under-ventilated fire whether at-grade [1], above-grade [9], or below-grade [8], fire growth followed which can increase the hazard to firefighters and potential occupants. Experiments conducted in purpose-built residential structures indicated that uncoordinated ventilation caused fire growth resulting in untenable conditions for firefighters 100 s after ventilation for a one-story residential structure and within 200 s after ventilation for a two-story residential structure [1]. Experiments 1C and 1D examined the impact of horizontal ventilation closely timed with the start of interior suppression; suppression occurred within 12 s and 9 s, respectively, of firefighters venting the fire room. Prior to ventilation, only smoke was visible through the window during both experiments. Ventilation of the bedroom window resulted in an immediate increase in visible burning within the fire room, and fire exhausted from the window, as shown in Figure 4.10. Fire continued to exhaust from the window until the suppression crew got water into the fire room.

(a) Window Prior to Ventilation - Experiment 1C

(b) Window Post Ventilation - Experiment 1C

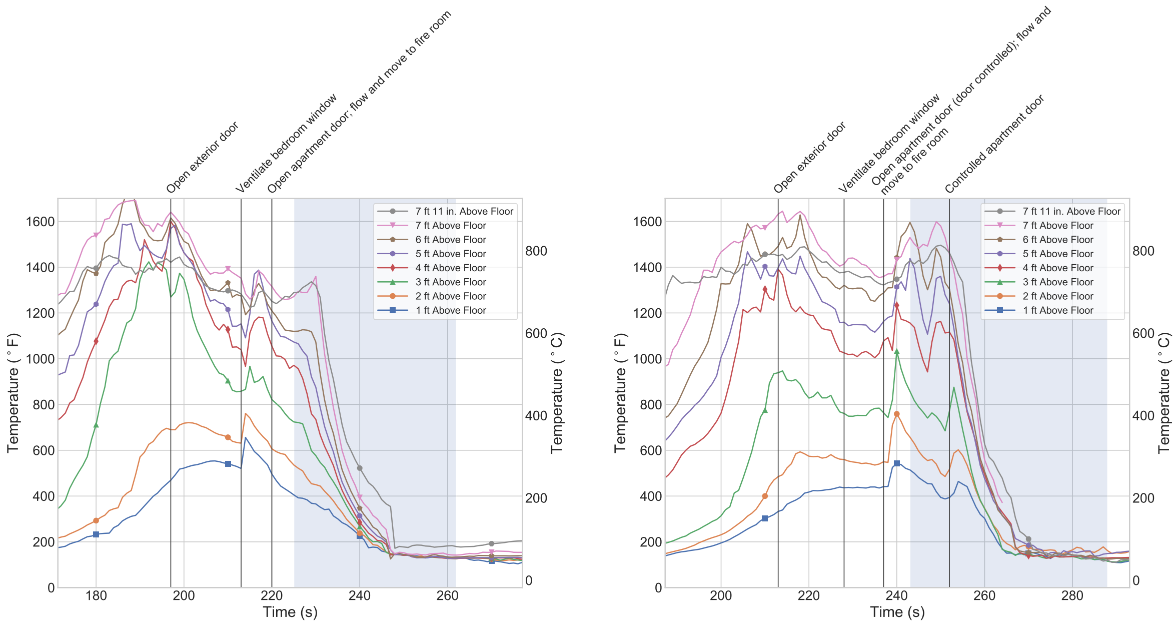
(c) Window Prior to Ventilation - Experiment 1D

(d) Window Post Ventilation - Experiment 1D

Figure 4.10: Changes in exterior conditions before and after horizontal ventilation in Experiments 1C and 1D.

Temperatures in the fire room (bedroom) for both experiments prior to horizontal ventilation were decreasing from their respective peak temperatures with living room oxygen concentrations at or below 15%. These combined factors are an indication the fire was likely in a state of ventilation-limited decay. Temperatures were stratified and ranged from 625 °F to 1260 °F in Experiment 1C (see Figure 4.11a), and from 435 °F to 1420 °F in Experiment 1D (see Figure 4.11b).

The increase in visible burning at the bedroom window corresponded to an increase in temperatures within the fire room. In Experiment 1C, fire room temperatures rose immediately following ventilation, increasing between 95 °F and 295 °F within the 10 s prior to interior suppression. In Experiment 1D, growth of a similar magnitude was observed, but temperatures did not begin to increase until roughly 10 s after horizontal ventilation, or just after the apartment door was opened. Fire room temperatures in Experiment 1D increased between 95 °F and 275 °F in the time period between opening the apartment door and interior suppression.



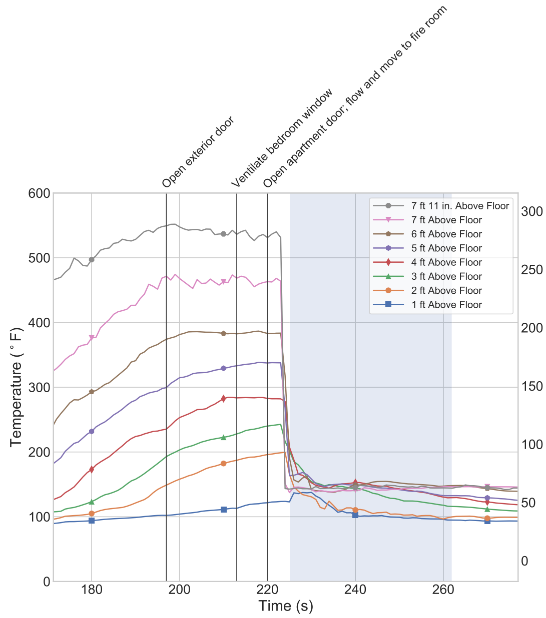
(a) Experiment 1C Fire Room Temperatures

(b) Experiment 1D Fire Room Temperatures

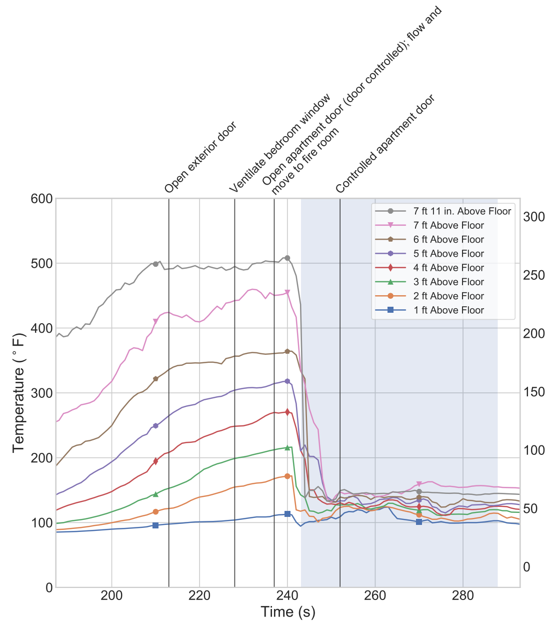
Figure 4.11: Temperatures within the fire room for Experiments 1C and 1D after the breezeway door was opened. Blue shaded areas indicate water flow.

Previous experiments that examined the coordination of ventilation and suppression in single-family dwelling fires demonstrated that while pre-suppression ventilation actions can result in fire growth within the fire room, conditions outside the fire room may improve as fresh air is entrained along the flow path [9]. Ultimately, the effects of pre-suppression ventilation depend on the flow paths created by ventilation openings in the structure, and the amount of time that elapses between ventilation and suppression.

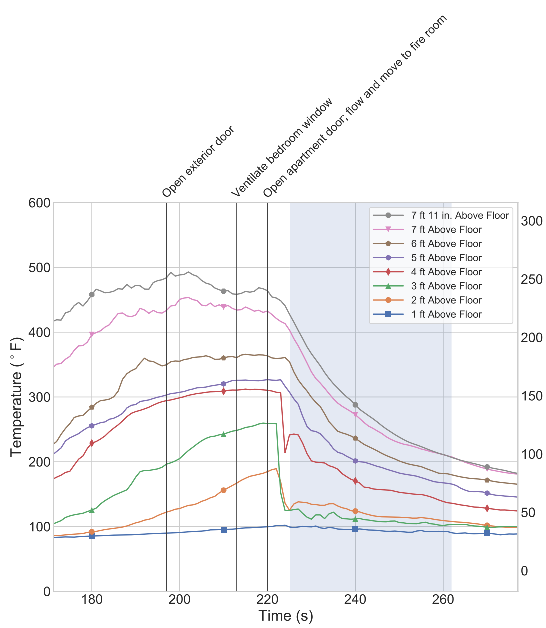
In both experiments, living room and kitchen ceiling temperatures were nominally steady (see Figure 4.12), while temperatures below 5 ft were increasing prior to ventilation of the fire room window. Generally, temperatures were stratified between approximately 100 °F and 550 °F. Despite the increase in fire room temperatures and visible burning from the bedroom window ventilation, there was no noticeable increase in temperatures in any compartment of the structure outside of the fire room in either experiment. The short time lag (10 s—12 s) between ventilation and suppression limited the spread of heat from the fire room throughout the fire apartment. Living room and kitchen temperatures remained steady until the apartment door was opened. The flow path created between the open apartment door and the fire room, in conjunction with the flow-and-move suppression, resulted in a decrease in temperatures along the flow path (i.e., in the living room and kitchen).



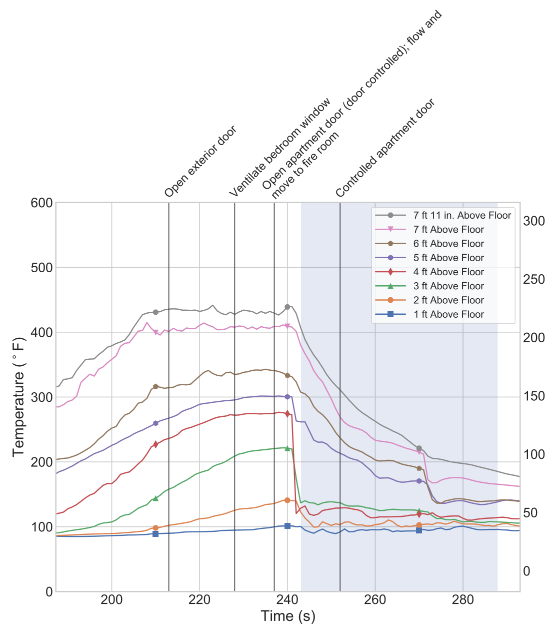
(a) Experiment 1C Kitchen Temperatures



(b) Experiment 1D Kitchen Temperatures



(c) Experiment 1C Living Room Temperatures



(d) Experiment 1D Living Room Temperatures

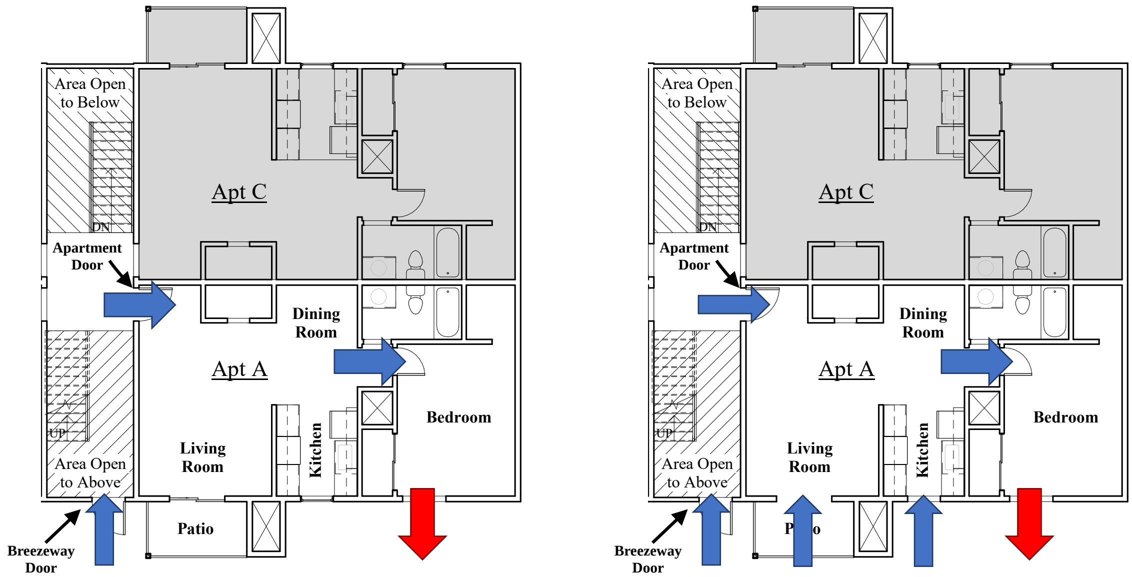
Figure 4.12: Temperatures within the kitchen and living room for Experiments 1C and 1D after the breezeway door was opened. Blue shaded areas indicate water flow.

4.5 Impact of Hydraulic Ventilation

Hydraulic ventilation was employed post-suppression in Experiment 1D using a combination nozzle with a narrow fog pattern, and in Experiment 4B using a 7/8 in. smooth bore nozzle. To quantify the impact of the air entrainment associated with hydraulic ventilation, the velocity probes at the apartment door and breezeway door were used in conjunction with thermocouples throughout the apartment. Differences in apartment volume (Experiment 4B was a second-floor unit with a high living room ceiling) and apartment ventilation prevent a direct comparison of the two nozzle types, but the impact of hydraulic ventilation can be compared to similar experiments that included natural ventilation and PPV. Previous research has been conducted to compare air entrainment as a function of stream type as part of the *Study of the Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Air Entrainment* [6].

To assess the impact of hydraulic ventilation in Experiment 1D, consider Experiment 1C, which was a similar scenario except for a lack of door control during suppression and hydraulic ventilation post-suppression. In both experiments, fire room temperatures had returned to near ambient conditions following suppression, but temperatures in the kitchen and living room remained elevated, greater than 120 °F, at 4 ft and above. In Experiment 1D, hydraulic ventilation began to lower temperatures within the kitchen within 4 s and the living room temperatures after 8 s. All temperatures had dropped below 100 °F in the kitchen within 29 s and living room within 75 s. In Experiment 1C, temperatures in the living room and kitchen did not drop below 100 °F until additional horizontal ventilation was provided at 91 s and 246 s for the kitchen and living room, respectively.

After the apartment door was opened for suppression in Experiments 1C and 1D, bi-directional flow was established at fire apartment door and breezeway door. In Experiment 1D hydraulic ventilation occurred 75 s after the apartment door was opened. At the start of hydraulic ventilation in Experiment 1D, the open exterior door was the inlet ventilation opening while the bedroom window was the outlet ventilation opening, as shown in Figure 4.13a. Additional horizontal ventilation was conducted 2 min after the start of hydraulic ventilation by opening the kitchen window and living room sliding glass door. Figure 4.13b shows how flows changed.



(a) Prior to Horizontal Ventilation

(b) Post Horizontal Ventilation

Figure 4.13: Flows during hydraulic ventilation during Experiment 1D. Red arrows indicate the flow of combustion products, and blue arrows indicate the flow of fresh air.

The open vents provided additional inlet vents into the apartment, which decreased the amount of air entrained from the stairwell. However, this ventilation configuration increased the air movement within the fire apartment because fresh air could be entrained directly into the apartment. Table 4.1 provides the range of velocities across the bi-directional probes located at the apartment door and breezeway door to compare natural ventilation (Experiment 1C), hydraulic ventilation (Experiment 1D), hydraulic ventilation with additional ventilation (Experiment 1D), and, for additional context, PPV (Experiment 2A).

Table 4.1: Impact of Narrow Fog Stream on Gas Flows

Exp.	Tactic	Apartment Door Velocity Range [m/s (mph)]	Breezeway Door Velocity Range [m/s (mph)]
1C	Natural Ventilation	-0.5 ↔ +1.0 (-1.1 ↔ +2.2)	-0.1 ↔ +0.5 (-0.2 ↔ +1.1)
1D	Hydraulic Ventilation	-2.0 ↔ -3.5 (-4.5 ↔ -7.8)	-1.5 ↔ -2.5 (-3.4 ↔ -4.5)
1D	Hydraulic w/ Horizontal Ventilation	-0.9 ↔ -1.4 (-2 ↔ -3.1)	-0.4 ↔ -1.5 (-0.9 ↔ -3.4)
2A	Positive Pressure Ventilation	-0.7 ↔ -2.7 (-1.6 ↔ -6)	-0.7 ↔ -8.8 (-1.6 ↔ -19.7)

(+) is out of the apartment/building; (-) is into the apartment/building

The impact of hydraulic ventilation can be seen by comparing the magnitudes of door velocities in Table 4.1, in which increasing magnitude indicates higher velocity and the sign indicates the direction. For the natural ventilation experiment (Experiment 1C), bi-directional flow (i.e., top of the door was exhaust (+) and bottom of the door was intake (-)) was persistent through the conclusion of the experiment. Hydraulic ventilation established unidirectional intake through the breezeway door and apartment door through air entrainment from the narrow fog stream. As additional ventilation occurred in the fire apartment (see Figure 4.13b), the magnitude through the apartment and breezeway doors dropped as local inlets were established in the fire apartment, though unidirectional flow was still established. For the experiments in which a 24 in. gasoline powered fan was positioned 6 ft from the breezeway door, unidirectional flow was also established. Although the magnitude of velocities at the breezeway door were higher in Experiment 2A compared to Experiment 1D due to the proximity of the fan, the range of apartment door velocities were similar.

Hydraulic ventilation also occurred in Experiment 4B with a smooth bore nozzle, rotated in an O pattern following initial suppression. The progression of the experiment dictated that additional horizontal ventilation occur before hydraulic ventilation, but that post-ventilation data can still be compared to Experiment 1D. The flow of gases was similar to Figure 4.13b. Door velocities after horizontal ventilation in Experiment 4B ranged between -0.7 m/s (-1.6 mph) and -1.3 m/s (-2.9 mph), similar to those in Experiment 1D. These results reinforce findings from a prior air entrainment study that showed that a stationary narrow fog stream and smooth bore stream rotated in an O pattern entrained similar amounts of air [6]. Because Experiments 4A and 4B were second-floor experiments, resulting in negligible flow velocities measured at the breezeway door due the distance from the fire apartment to the door.

Table 4.2: Impact of Straight Stream on Gas Flows

Exp.	Tactic	Apartment Door Velocity Range [m/s (mph)]
4A	Natural Ventilation	-0.7 ↔ +0.7 (-1.6 ↔ +1.6)
4B	Hydraulic with Horizontal Ventilation	-0.7 ↔ -1.3 (-1.6 ↔ -2.9)

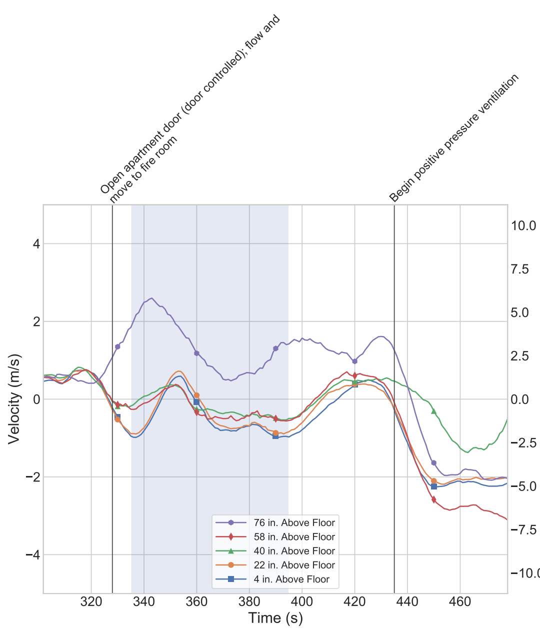
(+) is out of the apartment/building; (-) is into the apartment/building

In both hydraulic ventilation experiments, the entrainment from the hose stream was sufficient to create unidirectional flows through the fire apartment as measured by velocity probes at the doorway. Additional ventilation of the fire apartment unit led to a decrease of flow velocities at the door.

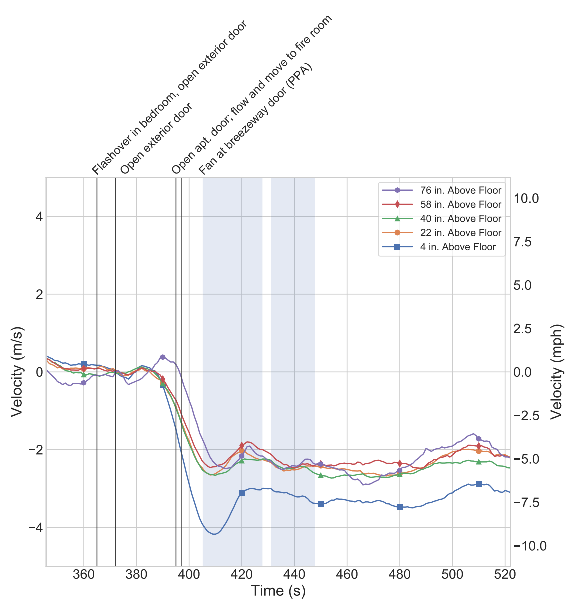
4.6 Positive Pressure Ventilation vs. Positive Pressure Attack

Experiments 2A and 2B examined the impact of utilizing a positive pressure ventilation fan post interior suppression (PPV) and simultaneous with interior suppression (PPA) on a first-floor bedroom fire, respectively. In both experiments, the bedroom window was removed prior to ignition, which created a vent ahead of the suppression crew. The vent also provided sufficient ventilation to the bedroom for fire to transition through flashover prior to fire department interventions. In both experiments, a 24 in. gasoline powered fan was positioned 6 ft from the breezeway door at full-tilt (approximately 20 deg.).

The difference in impact of PPV and PPA can be characterized by the conditions at the apartment doorway. In both experiments, post-flashover pressure in the fire apartment had reached approximately 2.5 Pa. During Experiment 2A, the pressure in the fire compartment was greater than the stairwell pressure, so products of combustion exhausted into the stairwell even with door control limiting flow (indicated by the positive gas velocities at the top of the doorway) until PPV occurred. During Experiment 2B, the positive pressure fan was activated 2 s after the apartment door was opened. The fan generated approximately 12.5 Pa of pressure in the stairwell, which was greater than the apartment pressure. This pressure difference limited the exhaust into the stairwell, indicated by negative velocities at all elevations within the doorway. Figure 4.14 shows the bi-directional velocity for the open apartment door in Experiments 2A and 2B.



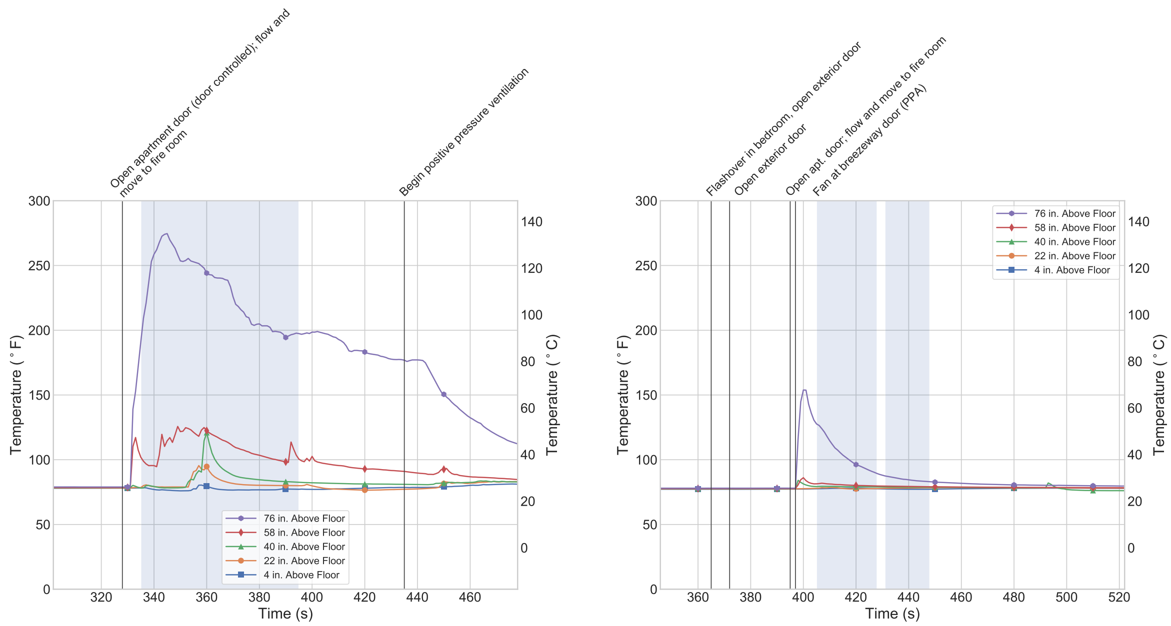
(a) Experiment 2A Door Velocities



(b) Experiment 2B Door Velocities

Figure 4.14: Apartment door velocities for Experiments 2A and 2B after the apartment door was opened. Blue shaded areas indicate water flow.

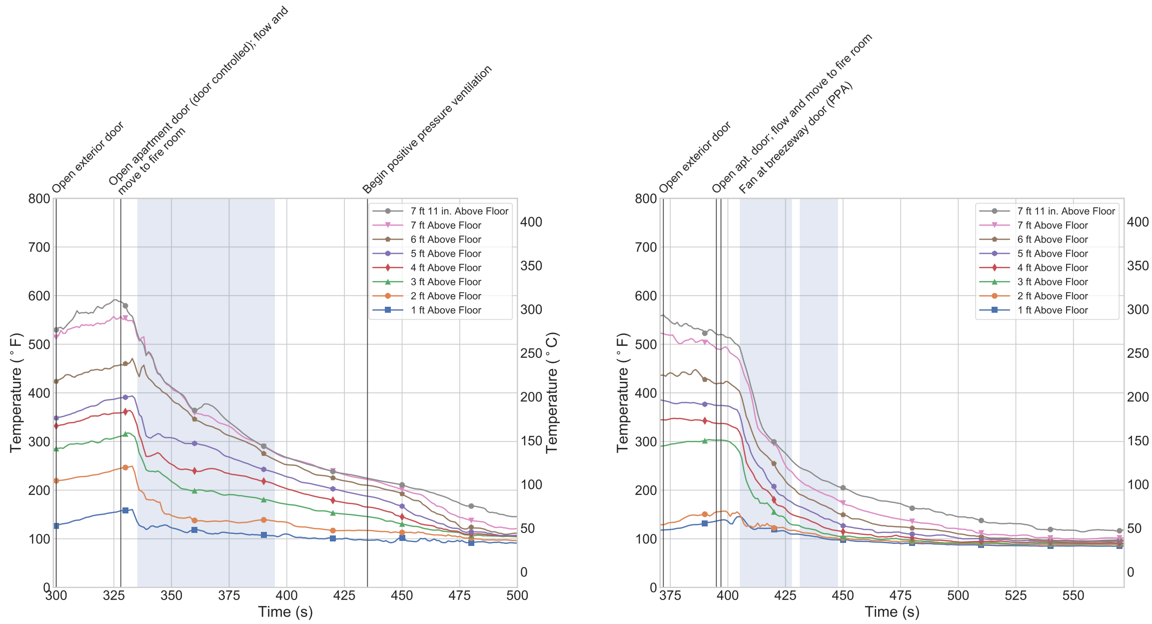
The differences in velocities directly relate the temperature conditions at the doorway. In both experiments, temperature in the living room ranged between 100 °F and 600 °F prior to opening the door. Door temperatures during Experiment 2A peaked to approximately 275 °F 76 in. above the floor, while door temperatures during Experiment 2B peaked to approximately 155 °F 76 in. above the floor (see Figure 4.15). Door control was able to limit the flow of gases at the door, and temperatures at the 58 in. elevation only rose to approximately 125 °F.



(a) Experiment 2A Door Temperatures (b) Experiment 2B Door Temperatures

Figure 4.15: Apartment door temperatures for Experiments 2A and 2B after the apartment was opened. Blue shaded areas indicate water flow.

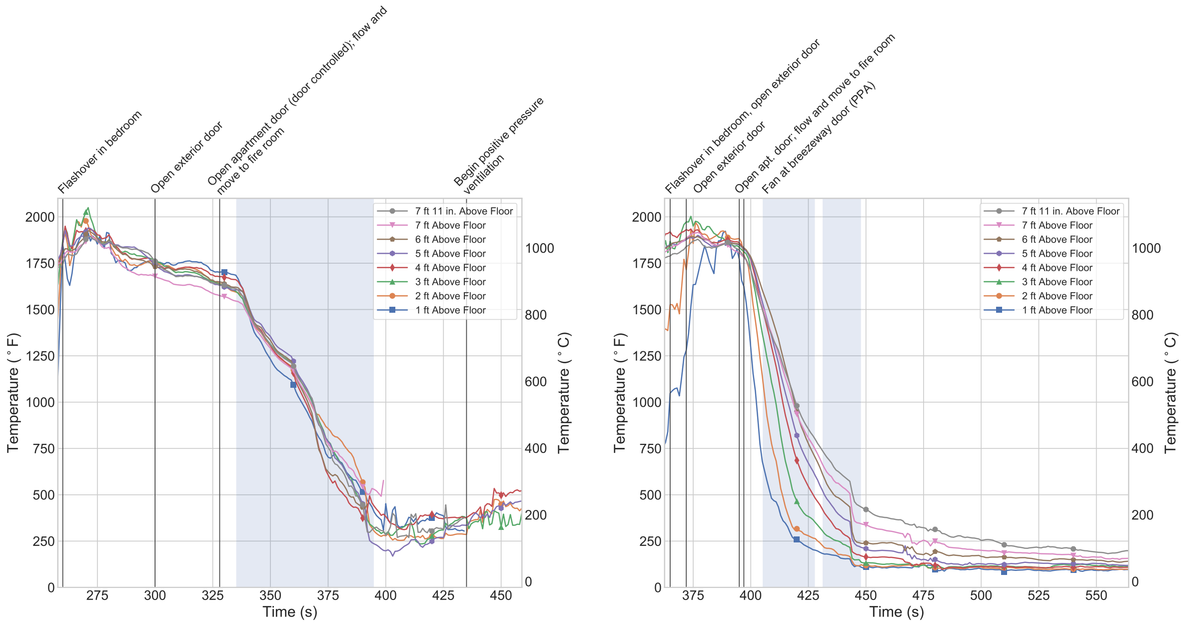
The living room temperatures during interior operations were similar for both experiments prior to suppression (see Figure 4.16). Living room temperatures in Experiment 2A did not decrease below 200 °F until approximately 132 s after the onset of suppression (25 s after PPV was initiated). In Experiment 2B, temperatures decreased below 200 °F approximately 58 s after suppression began. The combination of the entrained air from the flow-and-move suppression and the PPA in Experiment 2B resulted in a more rapid decline in temperatures between the doorway and the fire room in the apartment.



(a) Experiment 2A Living Room Temperatures (b) Experiment 2B Living Room Temperatures

Figure 4.16: Temperatures remote from the fire room for Experiments 2A and 2B after initial suppression. Blue shaded areas indicate water flow.

In both experiments, the flow-and-move suppression was the primary cause of decreased fire room temperatures from post-flashover magnitudes (approximately 1600°F) to tenable conditions for firefighter entry (below 500 °F, see Figure 4.17). The negligible amount of time between opening the apartment door and flowing water toward the fire room combined with either door control (Experiment 2A) or PPA (Experiment 2B) did not allow for any fire growth due to additional ventilation.



(a) Experiment 2A Fire Room Temperatures

(b) Experiment 2B Fire Room Temperatures

Figure 4.17: Fire room temperatures in Experiments 2A and 2B during suppression. Blue shaded areas indicate water flow.

4.7 Exposure to Occupant Location in Fire Apartment

In each experiment in Scenarios 1—4, gas concentrations were monitored 4 ft above the floor in the living room of the fire apartment. For the experiments in Scenarios 5 and 6, gas concentrations were monitored 4 ft above the floor in the second-floor target apartment. Figure 4.18 shows the increase in fractional effective dose (FED) from ignition to the time the breezeway door was opened as well as additional increase that occurred through theend of the experiment.

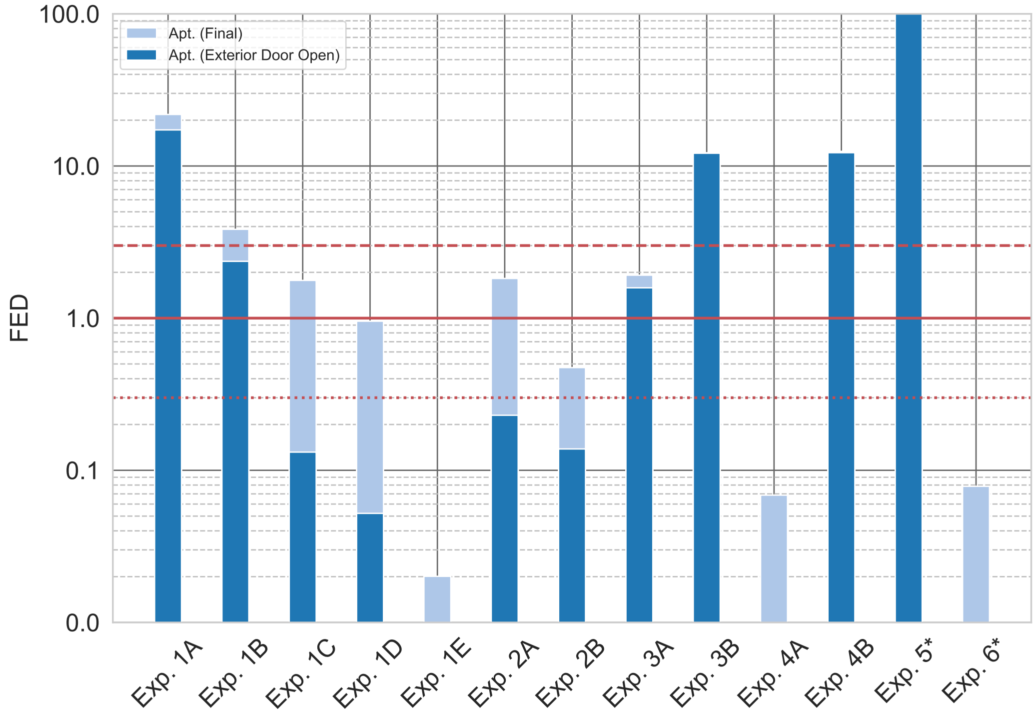


Figure 4.18: FED at occupant locations in the fire apartment at the time of fire department intervention (dark shaded bars) and at end of experiment (light shaded bars). Values are shown on a logarithmic scale to show detail at lower FED values. The dotted, solid, and dashed red lines denote FED = 0.3, FED = 1.0, and FED = 3.0, which are the thresholds for incapacitation for 11%, 50%, and 89% of the population, respectively.

Table 4.3 includes the time at which the breezeway door was opened and corresponding CO concentration and FED. Additionally, the table provides the final FED, time from breezeway door open for the CO concentration to drop below 0.12% (1200 ppm), and the time at which the peak rate of change of FED occurred. 0.12% (1200 ppm) is used as threshold as the CDC defines this to be the limit for an environment that is immediately dangerous to life or health concentrations (IDLH) [37].

Table 4.3: Exposure in Apartment Occupant Location

Exp #	Breezeway Door Time [s]	CO at Breezeway Door Open [ppm]	FED at Breezeway Door Open	Final FED	Time** to CO < 0.12% (1200 ppm) [s]	Time** to Peak FER [s]
1A	600	11,000	17	21.8	618	+
1B	600	4,300	2.4	4.8	434	23
1C	197	7,900	0.13	1.8	226	27
1D	213	4,100	0.05	0.95	147	34
1E	240	300	0.01	0.02	-	+
2A	300	6,700	0.23	1.8	210	36
2B	372	5,200	0.17	0.5	171	123
3A	1000	3,800	1.6	1.9	96	+
3B	816	8,200	12	12	43	+
4A	781	0	< 0.01	0.07	-	+
4B	569	11,000	12	13	198	+
5*	687	33,000	340	460	595	+
6*	656	3,500	< 0.01	0.07	211	46

** indicates the time is elapsed time from when breezeway door was opened
* indicates that measurement location was in second floor target apartment rather than in fire apartment
\+ indicates peak FER occurred at breezeway door open
\- indicates CO concentrations remained below 0.12% for duration of experiment

In the experiments in which the occupant location was in the fire apartment (Scenarios 1—4), the CO concentration at the time the exterior door was opened ranged from 0 ppm to 11,000 ppm, with a median concentration of approximately 5200 ppm. The gas concentrations resulted in FEDs ranging from 0 to 17, with a median FED of approximately 0.23. These ranges demonstrate the considerable variability in the toxic exposure to the living room occupant prior to any fire department intervention. The fire location, growth, and initial ventilation conditions in Scenarios 1—4 influenced the magnitude of FED observed at the time that the exterior door was opened.

The highest pre-intervention living room FEDs for the bedroom fire experiments (Scenarios 1 and 2) were observed in Experiments 1A and 1B, which were 17 and 2.4, respectively. These high FED values were due in part to the longer period prior to the entry of the suppression crew, which was 600 s in each experiment. Even though the fire in Experiment 1A had self-extinguished due to a lack of ventilation, it was that lack of ventilation that contributed to the high FED. As the fire in Experiment 1A entered a state of ventilation-limited decay, the products of combustion banked down to the floor level throughout the apartment. As a result, the toxic exposure to the occupant in the fire apartment continued to increase. In Experiment 1B, the fire also entered a ventilation-limited state of decay, but the open apartment door allowed combustion gases to fill the enclosed stairwell. Although the additional volume slowed the descent of the smoke layer in the apartment and corresponding rise in FED, the air in the stairwell prevented the fire from self-extinguishing and thus the FED still rose to 2.4 by the time the exterior door was opened. This open door also put potential occupants in the stairwell at risk.

The initial fire growth in Experiments 1C and 1D was similar to Experiments 1A and 1B (as described in Section 4.3), but the fire department intervention occurred earlier in the experiment timeline (197 s and 213 s, respectively compared to 600 s). The shorter timeline to entry and ventilation of the bedroom window (which allowed combustion gases to exhaust from the fire apartment) resulted in lower FEDs values. Although the FEDs at the time of intervention were lower (recall from Section 4.1 that FED is the impact of exposure over time), the gas layer had descended past the elevation of the living room sensor, as evidenced by the elevated CO concentrations of 7900 ppm and 4100 ppm, respectively.

The open fire room windows through the duration of Scenario 2 experiments combined with relatively late intervention times (300 s and 372 s for experiments 2A and 2B, respectively) led to higher FED quantities at the time of intervention than in Experiments 1C and 1D. However, FEDs were lower in Scenario 2 experiments than in Experiments 1A and 1B where there was no ventilation and longer times to intervention. This ventilation allowed combustion gases to exhaust the fire apartment for the duration of the experiments, but it also supplied additional oxygen, which allowed the bedrooms to transition to flashover.

The experiments in Scenarios 3 and 4, show the impact of fire location and fire growth on FED. Scenarios 3 and 4 were kitchen and living room fires on the first and second floor, respectively, that were controlled with different suppression tactics. The dichotomy in FED at the time the exterior door opened—1.6 and <0.1 for Experiments 3A and 4A, respectively and 12 for Experiments 3B and 4B, highlight these impacts. In Experiment 3A, a piece of dry wall fell in front of the open living room sliding glass door, which impacted the efficiency of the vent (i.e., it blocked the intake of air but allowed combustion gases to exhaust) and limited fire growth. In Experiment 4A, the drywall in the kitchen fell, which allowed combustion gases to flow into the attic space. The kitchen window did not completely fail, which limited the oxygen available for combustion and corresponding fire growth. These factors combined to limit the development of a smoke layer within the fire apartment.

For Experiments 3B and 4B where drywall failures did not impact fire growth, the FEDs were higher than the Scenario 2 experiments where there was similar pre-ignition ventilation. The fires in Scenario 2 were confined to the bedroom, whereas the fires in Scenarios 3 and 4 involved both the kitchen and the living room. The proximity of the gas sampling location to the seat of the fire and the extended pre-intervention growth in these experiments resulted in higher FEDs at the time of intervention.

The living room FED at the time of intervention had exceeded 1.0 in five out of the 11 experiments in Scenarios 1—4 (Experiments 1A, 1B, 3A, 3B, and 4B). In each experiment, the FED in the fire apartment continued to increase as firefighters initiated suppression and ventilation tactics. When evaluating the effects of fire department intervention, it is important to consider both the time to the peak FER and the magnitude of the increase in FED following intervention (i.e., how much worse conditions get after fire department actions).

The lowest final FED was observed in Experiment 1E, where the bedroom door swung closed prior to fire department intervention. Because the door closed while the smoke layer in the living room was still developing, gas concentrations, and the resulting FEDs, remained low in the living room for the remainder of the experiment. This result illustrated the effectiveness of a hollow-core bedroom door at limiting the amount of air that can be entrained to the fire room, reducing fire size. It also showed the effectiveness of the same door at minimizing the toxic exposure at remote locations in the fire apartment.

The peak FER was generally reached within 40 s of the opening of the exterior door. In Experiments 1A, 3A, 3B, 4A, 4B, and 5, the FER was already decreasing at the time of fire department intervention. The time from the exterior door opening to the peak FER was notably longer in Experiment 2B (PPA), with the peak FER being observed 123 s after the exterior door was opened. The longer period between intervention and peak was likely a result of mixing caused by the fan, which is consistent with previous experiments conducted in single-family dwellings [9]. It is worth noting that FED increased from 0.17 to 0.5, so magnitude of change was relatively small compared to all other Scenario 1 or 2 experiments (besides 1E) even with the longer time to reach peak.

Although in most of the experiments the peak FER was reached shortly after suppression and ventilation actions commenced, the rate at which the FER decreased varied among the experiments. The increase in the FED from the time of intervention to the end of the experiment reflected the effectiveness of suppression and ventilation tactics at reducing the exposure in the living room of the fire apartment. The changes in how quickly the FED increased following suppression in the living room/kitchen experiments (Scenarios 3 and 4) was generally less than the increase observed after suppression of the bedroom fires in Scenarios 1 and 2. One reason for this was the difference in ventilation configurations between the two experiments. In the living room/kitchen fires, the suppression crew had immediate access to the fire, meaning that suppression actions, whether from the interior or exterior, were initiated shortly after fire department intervention. As suppression actions began to take effect, entrained air from the apartment door and living room sliding glass door began to improve conditions in the area of the gas sample point. In the bedroom fires, on the other hand, the suppression crew had to advance to the bedroom doorway to extinguish the fire.

In Experiments 1A and 1B, the apartment doorway was the only opening through which fresh air could be entrained and products of combustion could be exhausted, resulting in larger increases FED (4.5 and 2.4, respectively) than in the other bedroom fire experiments. Additionally, CO concentrations in the fire apartment remained above 0.12% (1200 ppm) for 618 s and 434 s in Experiments 1A and 1B, respectively—longer than the remainder of the Scenario 1—4 experiments. In the remaining bedroom fire experiments (Experiments 1C, 1D, 2A, and 2B), the only ventilation points within the fire apartment were the apartment doorway and the bedroom window. Although this ventilation configuration resulted in more efficient ventilation than in Experiments 1A and 1B, the improvement in conditions was not as rapid as in the Scenario 3 and 4 kitchen/living room experiments. The minimal increase in FED following intervention in the Scenario 3 and 4 experiments illustrated the importance of suppression in improving conditions for occupants potentially trapped within the structure. Similarly, the increase in FED following intervention in the Scenario 1 and 2 experiments demonstrated the importance of search to locate and quickly remove occupants to minimize their potential exposure.

In Experiments 5 and 6, gas concentrations were measured in a target apartment on the second floor of the structure rather than in the fire apartment itself. These experiments examined the effects of interior and exterior fire spread, respectively, on thermal conditions remote from the fire room. In Experiment 5, the gas sample point was located in a second-floor apartment (Apartment F), and the doors between this apartment and the lower-level fire apartment and the common stairwell were open at the time of ignition. As the fire grew, products of combustion began to fill Apartment F, but the FED did not substantially increase until after the living room sliding glass door was opened. This action completed a flow path with the exhaust traveling up the common stairwell through Apartment F and out the sliding glass door. The FED at the living room occupant location was the most severe exposure observed during this series of experiments, with a peak CO concentration in excess of 33,000 ppm.

In Experiment 6, gas concentrations were also measured in a second-floor apartment (Apartment G) with the living room sliding glass door open from the time of ignition. The intent of Experiment 6 was to examine the effects of exterior, balcony-to-balcony spread on the conditions inside the exposure apartments. Despite the open living room sliding glass door, the gas concentrations in the living room of the second floor apartment did not begin to significantly increase in Experiment 6 until late in the experiment, after exterior suppression had been initiated, resulting in a comparatively low FED.

4.8 Exposure to Occupant Location in Common Stairwell

In multi-family dwellings, firefighters must not only consider the exposure to potentially trapped occupants within the fire apartment, but also the exposure to occupants in the common stairwell. Allowing products of combustion to collect in the stairwell can jeopardize the egress of occupants trapped in other apartments within the structure while complicating operations for firefighters in exposure apartments. In each experiment, gas concentrations were measured 4 ft above the floor on the lower-level, first-floor, and second-floor landings in the common stairwell. FED at each location at the time that the exterior door was opened and at the end of the experiments are shown in Figure 4.19. For each experiment and location within the stairwell, Table 4.4 lists the CO concentration and resulting FED at the time the breezeway door was opened, as well as the FED at the end of the experiment, the time from breezeway door opening until the CO concentration dropped below 0.12% (1200 ppm), and the time from the exterior door opening until the peak FER was observed. 0.12% (1200 ppm) is used as threshold as the CDC defines this to be the limit for an environment that is immediately dangerous to life or health concentrations (IDLH) [37]. Experiment 6 is not included in either Figure 4.19 or Table 4.4 because gas measurements were only made in the exposure apartment.

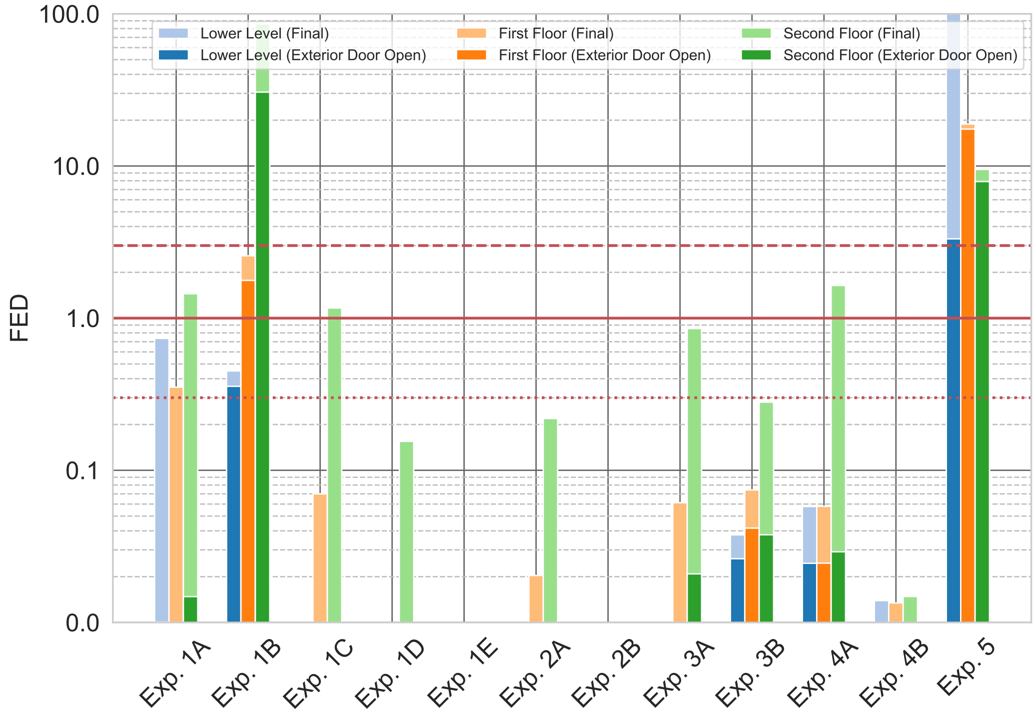


Figure 4.19: FED at occupant locations in the stairwell at the time of fire department intervention (dark shaded bars) and at end of experiment (light shaded bars). Values are shown on a logarithmic scale to show detail at lower FED values. The dotted, solid, and dashed red lines denote FED = 0.3, FED = 1.0, and FED = 3.0, which are the thresholds for incapacitation for 11%, 50%, and 89% of the population, respectively.

In all experiments except 1B and 5, the fire apartment door remained closed from the time of ignition to fire department intervention. In these experiments, the CO concentrations and FEDs measured in the stairwell prior to intervention were negligible (FED $\ll 0.1$), as shown in Table 4.4 and Figure 4.19, indicating the apartment doors were effective at maintaining a barrier between the apartment and the stairwell, even as fires burned for several minutes in a post-flashover state within the apartments. In contrast, the two experiments where the fire apartment door was open from ignition, FEDs in the stairwell prior to firefighter entry exceeded the lowest threshold for incapacitation potential, ranging from 0.4 to 31.

In each of these experiments, the apartment door was opened by firefighters to either begin or complete suppression efforts. By opening the front door to enable extinguishment, the isolation that was previously afforded by the closed door was removed, allowing products of combustion to spill into the stairwell. Although the amount of products of combustion exhausted into the stairwell varied depending on the fire location and tactics utilized, FED at the stairwell measurement locations increased in each experiment. Increases in FED following the opening of the apartment door were only observed at or above the level of the fire apartment. Appreciable increases in the FED were not observed when the sample point was lower than the fire apartment (i.e., the lower level

Table 4.4: Exposure at Stairwell Occupant Locations

Exp #	Location	Breezeway Door Time [s]	CO at Breezeway Door [ppm]	FED at Breezeway Door Open	Final FED	Time** to Peak FER [s]	Time** to CO < 0.12% (1200 ppm) [s]
1A	Second Floor	600	-	0.01	1.5	490	646
	First Floor	600	-	0.01	0.35	409	463
	Lower Level	600	-	0.01	0.74	402	579
1B	Second Floor	600	20,000	31	86	+	944
	First Floor	600	4,700	1.8	2.6	+	222
	Lower Level	600	-	0.4	0.45	+	925
1C	Second Floor	197	-	< 0.01	1.2	283	422
	First Floor	197	-	< 0.01	0.07	365	374
	Lower Level	197	-	< 0.01	0.01	*	*
1D	Second Floor	213	-	< 0.01	0.15	116	122
	First Floor	213	-	< 0.01	0.01	*	*
	Lower Level	213	-	< 0.01	< 0.01	*	*
1E	Second Floor	240	-	< 0.01	< 0.01	*	*
	First Floor	240	-	< 0.01	< 0.01	*	*
	Lower Level	240	-	< 0.01	< 0.01	*	*
2A	Second Floor	300	-	< 0.01	0.22	159	226
	First Floor	300	-	< 0.01	0.02	181	-
	Lower Level	300	-	< 0.01	0.01	-	-
2B	Second Floor	372	-	< 0.01	< 0.01	-	-
	First Floor	372	-	< 0.01	0.01	-	-
	Lower Level	372	-	< 0.01	0.01	*	*
3A	Second Floor	999	600	0.02	0.85	125	379
	First Floor	999	100	< 0.01	0.06	34	*
	Lower Level	999	-	< 0.01	< 0.01	-	-
3B	Second Floor	816	300	0.03	0.28	96	126
	First Floor	816	200	0.04	0.07	23	*
	Lower Level	816	100	0.02	0.03	145	*
4A	Second Floor	781	200	0.02	1.6	138	236
	First Floor	781	100	0.02	0.06	*	*
	Lower Level	781	100	0.02	0.06	*	*
4B	Second Floor	569	-	< 0.01	0.01	*	*
	First Floor	569	-	< 0.01	0.01	-	-
	Lower Level	569	-	< 0.01	0.01	-	-
5	Second Floor	687	10,000	7.9	9.5	+	238
	First Floor	687	10,000	18	19	+	292
	Lower Level	687	3,500	3.3	270	1360	211

** indicates the time is elapsed time from when breezeway door was opened
+ indicates peak FER occurred at front door open
- indicates CO concentration did not exceed 100 ppm
* indicates CO concentrations remained below 0.12% for duration of experiment

for experiments other than 1A, 1B, and 5, or the first floor apartment for Experiments 4A and 4B).

Regardless of the level of the fire apartment, the second-floor stairwell location was the area of greatest exposure within the common stairwell, and was characterized by the highest FED by the end of the experiment and the longest time from intervention until the peak FER was observed. Unlike the fire apartment FERs, which generally reached a peak within 40 s of the breezeway door opening, the FERs within the stairwell, and particularly on the second-floor landing, did not peak until 96 s–490 s after the exterior door was opened. The longer time between intervention and peak FER in the stairwell indicated that even as suppression and ventilation were beginning to improve conditions within the apartment, they were continuing to deteriorate in the stairwell. Further, the lack of doors and windows in the stairwell delayed the process of ventilation, as reflected by the longer time to peak FER and longer time until the CO concentrations dropped below 0.12% (1200 ppm).

Experiment 1A showed the extent of stairwell contamination if no actions were taken to mitigate the spread of smoke into the stairwell. Although the fire had self-extinguished due to a lack of oxygen prior to fire department intervention, FEDs increased considerably to 0.74, 0.3, and 1.5 at the lower level, first floor, and second floor, respectively. At each level, these increases in FED were among the highest observed out of the Scenario 1—4 experiments.

In Experiments 1D, 2A, and 2B, firefighters took actions to ventilate or mitigate exposure to the stairwell while suppression actions were being conducted in the fire apartment. In Experiment 1D, the door was controlled after the suppression crew entered the fire apartment, and was only re-opened once the bedroom fire was extinguished and hydraulic ventilation was initiated. The door control resulted in a comparatively lower second-floor landing FED (0.15) compared to Experiment 1C (1.2), where door control was not conducted. Experiments 2A and 2B examined the effects of PPV and PPA, respectively, at reducing exposure to the stairwell. As described in Section 4.6, the delay between suppression and the activation of the positive pressure fan in Experiment 2A resulted in a larger amount of exhaust from the fire apartment into the stairwell compared to Experiment 2B. The immediate introduction of the positive pressure fan in Experiment 2B limited the exhaust from the fire room to the stairwell, resulting in a negligible second-floor FED in Experiment 2B (FED < 0.01). Note that in each of the bedroom fire experiments where actions were taken to reduce exposure in the stairwell, the FED at each measurement location in the stairwell remained below 0.3.

Scenarios 3 and 4 examined the differences between exterior and interior suppression on first- and second-floor kitchen/living room fires, respectively. In Experiments 3A and 4A, the initial fire department intervention was opening the exterior breezeway door, after which the suppression crew opened the apartment doorway and began suppression. In Experiments 3B and 4B, the initial fire department intervention was exterior suppression, after which the suppression crew entered the breezeway and opened the apartment door to complete extinguishment. The FEDs at the second-floor landing location at the time of intervention for the two interior attack experiments were higher (0.85 and 1.6 for Experiments 3A and 4A, respectively) than the experiments in which exterior fire control was performed prior to interior attack (0.28 and 0.01 for Experiments 3B and 4B, respectively). The lower stairwell exposures in these experiments suggested that the exterior suppression action was effective at contracting hot gases and wetting fuel surfaces, reducing the rate at which products of combustion were produced. Further, in the time that elapsed between the end of exterior suppression and the opening of the apartment door, products of combustion were able to exhaust from the fire apartment through other openings, reducing the amount of smoke exhausted into the stairwell. Conversely, in the interior attack experiments, suppression started as the apartment door was opened, meaning products of combustion could freely exhaust into the stairwell as suppression actions began to take effect.

In the experiments where the fire apartment door remained closed prior to intervention, the peak FEDs observed in the stairwell were far less than in the living room of the fire apartment. Further, the increase in FED at the measurement locations following intervention was generally less than the thresholds for incapacitation. The second-floor FED exceeded 1.0 (which potentially incapacitates 50% of the population) by the end of the experiment in four out of the 10 Scenario 1—4 experiments. The FEDs on the first floor and lower level did not exceed 1.0, with the exception of Experiment 1B. It is important to note, however, that although the conditions in the stairwell did not always reach the threshold for incapacitation, the reduced visibility and irritant nature of the gases could complicate egress for occupants in exposure apartments. These conditions could also hamper firefighting operations outside of the initial fire apartment, such as search and overhaul.

In Scenarios 1—4, the highest FEDs at the gas measurement locations in the stairwell were observed in Experiment 1B, in which the door between the stairwell and the apartment was open from the time of ignition, allowing products of combustion to exhaust into the stairwell for the duration of the experiment. As the lower-level bedroom fire grew, products of combustion filled the stairwell from the top down, while the air that had filled the stairwell was entrained into the fire apartment. This resulted in higher FEDs at the time of intervention on the first- and second-floor landings (1.8 and 31, respectively) than at the lower-level measurement location (0.4). The FED at each location continued to increase after fire department intervention due to the volume of smoke exhausting from the fire apartment and lack of effective ventilation in the stairwell. By the end of the experiment, the FED had increased to 0.45, 2.6 and 86 at the lower-level, first-floor, and second-floor measurement locations, respectively. The high toxic exposures that would be observed at these locations illustrate the hazard that a lack of stairwell isolation poses to occupants may be trapped in apartments remote from the fire apartment. If the stairwell were compromised as a means of egress, occupants of these remote apartments may need to find a secondary means of egress, possibly including fire department ladders.

4.9 Interior and Exterior Fire Spread

Two key features of these acquired apartment buildings, the purpose-built enclosed stairwell (i.e., the egress path) and the combustible wood balconies, were useful for experiments designed to examine interior and exterior fire spread from a lower-level apartment fire. Instead of a single experiment looking at both interior and exterior fire spread concurrently, multiple experiments were conducted to decouple the pathways for fire growth and better identify particular hazards of interior spread (Experiments 1B and 5) and exterior spread (Experiment 6).

4.9.1 Interior Fire Spread - Experiments 1B and 5

Experiments 1B and 5 were both designed to examine interior spread from a lower-level apartment (Apartment J) through the enclosed stairwell. The differences between the experiments was ventilation and fire location within the apartment. The only ventilation for the bedroom fire in Experiment 1B was an open apartment door and eventual exterior stairwell door as part of firefighter intervention. For the living room fire in Experiment 5, the apartment door and living room sliding glass door were open as well as the apartment doors to two second-floor apartments (Apartment H and Apartment F). Additional changes to ventilation included closing the Apartment H door and opening the Apartment F living room sliding glass door before opening the exterior stairwell door for firefighter intervention.

Although the ignition location varied, the total fuel load in each experiment was similar, allowing for a comparison between the experiments to examine the impact of ventilation. Additionally, both experiments had similar instruments in the apartment of origin and common stairwell. To compare the impact of ventilation, the focus was on temperatures 3 ft and 5 ft above the floor in the second-floor apartments (Experiment 5 only), and 3 ft and 5 ft at each floor in the stairwell to represent the conditions at firefighter crawling and standing height, respectively. In the fire room, the top and bottom thermocouple (1 ft and 7 ft, 11 in. above the floor) in the fire room was used as an indicator for flashover.

In Experiment 5, the door to Apartment H was closed 340 s (5:40) after ignition. Prior to this, the smoke movement in the structure was similar to Experiment 1B. Buoyant gases exhausted from the fire apartment, rose through the stairwell, and filled from the top down. The larger volume to fill Experiment 5, due to the open second-floor apartments, impacted the rate at which the stairwell filled with smoke. As the stairwell began to accumulate smoke, the gas layer reached the top of the door frames to Apartments F and H and began to spill into those apartments. The conditions immediately prior to closing the apartment door to Apartment H are indicated in Figure 4.20.

(a) Experiment 1B (b) Experiment 5

Figure 4.20: Fire apartment and stairwell temperatures for Experiments 1B and 5. Experiment 5 includes target apartment (F and H) living room temperatures. Data are presented 340 s post-ignition, which was prior to Apartment H door closing in Experiment 5. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

In both experiments, the room of origin had the highest temperatures, and 340 s after ignition, neither had transitioned through flashover. Outside of the fire apartment, temperatures were greatest in the lower-level stairwell location, and they decreased as the distance from the fire apartment increased. The temperatures in the first and second floor of the stairwell were elevated but were on the low end of the ordinary operating class for firefighter exposure. In Experiment 5, the temperatures at both crawling and standing heights in the second-floor apartments remained below 81 °F as the cool air at the start of the experiment mixed and cooled the combustion gases that began to fill the units.

In Experiment 5, closing the door to Apartment H isolated it from the common stairwell, which continued to fill with smoke. Temperatures in Apartment H at both firefighter crawling and standing heights remained low for the remainder of the experiment. In the 75 s between the closing of the Apartment H door and the opening of the living room sliding glass door in Apartment F, the fire apartment (Apartment J) transitioned through flashover. Temperatures continued to increase in Apartment F and at all three locations in the stairwell (see Figure 4.21).

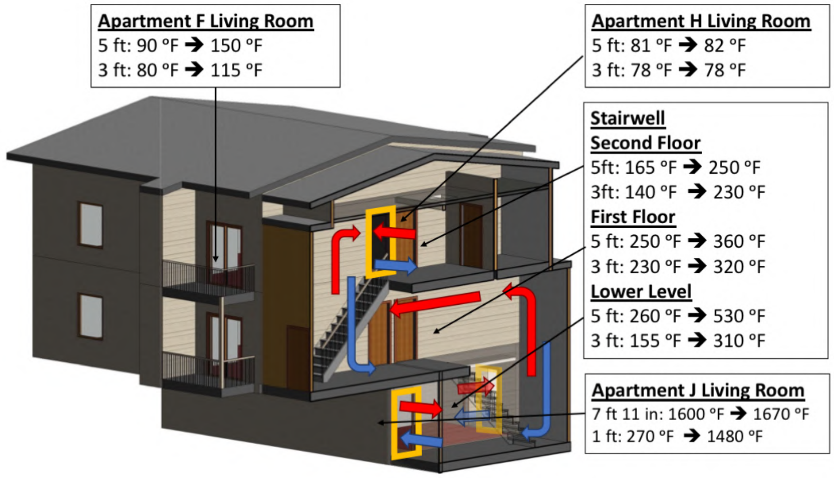


Figure 4.21: Fire apartment and stairwell temperatures for Experiment 5. Data are presented at 340 s post-ignition, which was prior to Apartment H door closing, and at 417 s post ignition, which was prior to the sliding glass door in Apartment F being opened. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

At 600 s in Experiment 1B, the exterior stairwell door was opened, and at 417 s in Experiment 5, the living room sliding glass door in Apartment F was opened. These times represented the first change in additional exterior ventilation following ignition. Figure 4.22 shows the change in temperatures in the fire room, stairwell, and applicable exposure units in the 30 s that followed the ventilation action: 600 s–630S in Experiment 1B and 417 s–447 s in Experiment 5.

(a) Experiment 1B (b) Experiment 5

Figure 4.22: Fire apartment and stairwell temperatures for Experiments 1B and 5. Experiment 5 includes target apartment (F and H) living room temperatures. Data are presented from 600 s–630 s post-ignition for Experiment 1B following the stairwell door being opened and from 417 s–447 s post-ignition for Experiment 5, which was after the Apartment F sliding glass door was opened. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

The impact of opening exterior vents resulted in different behavior in the two experiments, despite the vent creating a new flow path in both cases. For Experiment 1B, a new flow path was created in which the upper portion of stairwell door acted as an exhaust for high-pressure combustion gases that accumulated in the stairwell, and the bottom portion of the door acted as an intake of low pressure air (see Figure 4.22a). Without ventilation to the lower-level apartment fire in Experiment 1B, the fire had begun to decay due to a lack of oxygen. Because the stairwell door was the only open vent (serving as the only intake and exhaust), and due to the timing of the vent opening and its proximity to the fire (a lower-level bedroom fire), there was minimal impact on the fire dynamics. Temperatures within the stairwell and fire apartment continued to decrease. The suppression crew observed conditions at the doorway and in the stairwell for 15 s, then entered the structure and proceeded downstairs to the door of the fire apartment. The suppression crew entered the fire apartment and simultaneously began flowing water at 660 s.

In Experiment 5, the open exterior vent had a different effect compared to Experiment 1B. Temperatures in Apartment F were consistent with the ordinary exposure category for firefighters at the time the sliding door was opened (see Figure 4.22b) [33]. When the sliding door to Apartment F was opened, a new flow path was created with the inlet in the fire apartment at the sliding glass door and the exhaust at the sliding glass door in Apartment F. The flow path included the common stairwell and the living room of Apartment F. The living room was in the exhaust of this flow path, which was the reason for the high temperatures in these locations. Within 30 s of the opening of the sliding glass door in Apartment F, living room 3 ft temperatures increased from 115 °F to 175°F and 5 ft temperatures increased from 150 °F to 235 °F. Similar increases were observed in the stairwell, as shown in Figure 4.22b. At the first-floor measurement location in particular, temperatures 3 ft above the floor increased from 310 °F (ordinary operating class) to 360 °F (emergency operating class), and the temperature 5 ft above the floor increased from 310 °F to 900 °F in 30 s.

Temperatures in the stairwell and Apartment F continued to increase after the opening of the sliding glass door, peaking before the exterior stairwell door was opened and suppression began. Figure 4.23 shows the change in temperatures in the 58 s from the start of interior suppression until the start of exterior suppression. The Apartment F living room temperatures reached peaks of 490 °F and 590 °F at 3 ft and 5 ft, respectively. These temperatures were consistent with the lower threshold of the emergency operating class, indicating firefighters operating in these conditions without the protection of a hoseline would be at risk of thermal injury in within a short time frame [33].

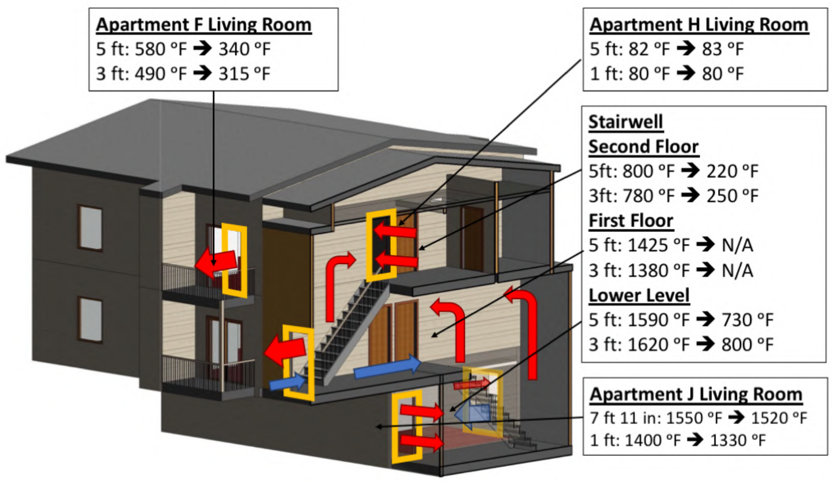


Figure 4.23: Fire apartment and stairwell temperatures for Experiment 5. Data are presented at 687 s post-ignition, which was prior to the opening of the stairwell door and starting suppression, and at 745 s post-ignition, which was prior to the start of exterior suppression. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

As the suppression crew made entry and began flowing water, temperatures in the stairwell and Apartment F began to decrease, but they remained above 300 °F at each location. Interior suppression was limited in effectiveness on decreasing the lower-level stairwell temperatures, which remained between 700 °F–800°F, and was ineffective at reducing temperatures in the fire apartment. Although temperatures began to decrease in the stairwell, the suppression crew was unable to advance to the top of the stairs due to high heat.

Exterior water application reduced temperatures in the fire apartment to less than 600 °F within 15 s because the water was able to directly impact the burning fuels. By 980 s post-ignition (235 s after the start of combined interior and exterior suppression), temperatures in the stairwell were reduced from 800 °F to 425 °F on the lower-level, but increased from 250 °F to 410 °F on the second-floor landing, as shown in Figure 4.24. The initial interior suppression dropped the second-floor stairwell temperatures due to initial gas cooling. As the suppression crew was able to advance to the fire room, combustion gases still flowed into the stairwell. Temperatures in Apartment F decreased to 270 °F at both 3 ft and 5 ft because the living room was in the flow path and the gases mixed with cool air entrained by the open front door. The second-floor thermocouples were offset (further onto the landing) from the flows that traveled through the open apartment door, and therefore remained elevated for a longer duration.

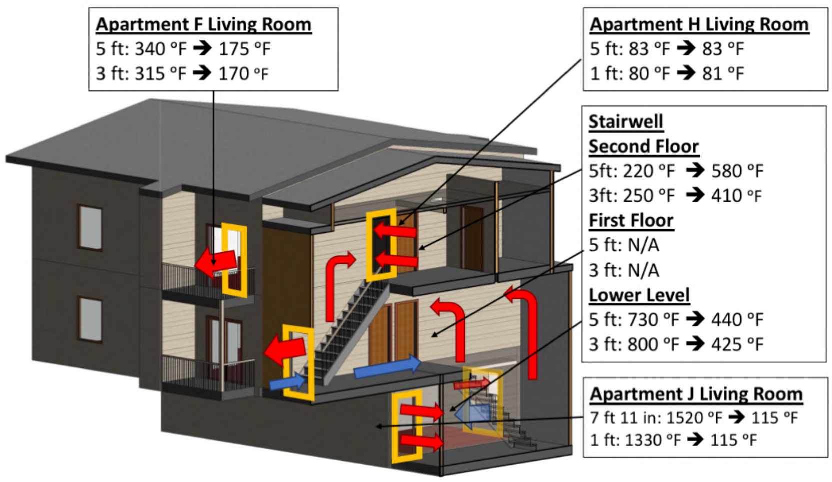


Figure 4.24: Fire apartment and stairwell temperatures for Experiment 5. Data are presented at 745 s post-ignition, which was prior to the start of exterior suppression, and at 980 s post-ignition, which was when the interior suppression crew was able to get water directly on the living room contents. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

Although peak temperatures in the stairwell prior to interior suppression exceeded 1100 °F, consistent with the onset of flashover, the smoke was too fuel-rich to allow flaming combustion. This was the case for both the stairwell and in Apartment F. Despite this, considerable damage was observed in the stairwell and Apartment F after the experiment. The elevated temperatures caused the steel steps leading from the first floor to the lower level to deform and separate from the floor landing and vertical stair wall, as shown in Figure 4.25.

(a) Warped Railing (b) Deformed Treads

Figure 4.25: Lower-level stair deformation during Experiment 5.

In Experiment 5, when the new flow path was created by the opening of the Apartment F sliding glass door, temperatures quickly increased and continued to do so until suppression began. Temperatures in Apartment F were sufficiently elevated to pyrolyze the upholstered furniture in the living room (as shown in Figure 4.26), but oxygen concentrations were too low to sustain flaming combustion. Oxygen concentrations reached a minimum value of 4.2% 658 s post ignition, prior to the start of interior suppression. After the exterior door to the structure was opened, oxygen concentrations in Apartment F immediately increased, but water flow reduced temperatures below 300 °F, which prevented flaming combustion.

Figure 4.26: Pyrolyzed furniture located in the living room of Apartment F during Experiment 5.

The high temperatures measured in Experiment 5 at the time the exterior breezeway door was opened and just prior to interior suppression (1425 °F and 800 °F at 3 ft on the first and second floors, respectively) would have been untenable for firefighters in full PPE for a sustained duration. Constant water flow in the stairwell by the suppression crew reduced temperatures, but the layout of the structure prevented water from reaching the lower-level fire apartment from the first-floor landing. The suppression actions in the stairwell could provide localized cooling, but effective suppression in the fire apartment was not possible until water was applied from an exterior position on side C into the living room of Apartment J. Following exterior suppression, conditions rapidly improved throughout the structure.

Results of this experiment are consistent with previous research conducted on basement and below-grade fires [8], which have emphasized that basement and below-grade fires should be fought from their own level to avoid placing crews in the exhaust portion of the flow path whenever possible. Previous research [7, 8, 38] has also emphasized the effectiveness of closed doors at maintaining tenable conditions in an isolated compartment. After the door to Apartment H was closed, temperatures in the apartment did not exceed 110 °F at any elevation and remained below 85 °F at 3 ft and 5 ft for the duration of the experiment. The thermal conditions in the closed apartment were in contrast to those observed in the common stairwell and in Apartment F, which exceeded 495 °F at their peak. The difference in thermal conditions between the isolated and open compartments illustrated the effectiveness of a closed door in maintaining the tenability of the space for occupants, and also for firefighters. Further, recall that the door to Apartment H remained opened until 340 s after ignition. The act of closing the previously opened door was able to maintain tenability in the space.

4.9.2 Exterior Fire Spread - Experiment 6

Experiment 6 was conducted to examine exterior spread from a lower-level apartment fire (Apartment I). Of particular interest was the spread from the apartment of origin to fuel on the balcony and the how the fire would spread if the fuel on the lower-level balcony ignited. The sliding glass door in the lower-level apartment was open at the time of ignition, and the door between the fire apartment and the common stairwell was closed, which isolated the apartment from the stairwell for the duration of the experiment. Two target apartments located above the fire apartment (Apartment C on the first floor and Apartment G on the second floor) were instrumented to quantify the impact of vertical spread. Prior to ignition, the sliding glass door was closed in Apartment C (a first-floor apartment) and was open in Apartment G (a second-floor apartment).

The kitchen window in Apartment I was vented at 461 s, and flames began to extend to the exterior from the Apartment I sliding glass door approximately 470 s after ignition. The living room transitioned through flashover at 510 s. As the fire continued to exhaust from the Apartment I sliding glass door, the first- and second-floor balconies (Apartments C and G) were ignited 524 s and 583 s after ignition, respectively. Figure 4.27 shows a time lapse of the exterior flame spread in Experiment 6 from the time the kitchen window was vented to 15 s after exterior suppression was started.

(a) 461 s Post Ignition – Kitchen Window Vented

(b) 490 s Post Ignition

(c) 520 s Post Ignition

(d) 550 s Post Ignition

(e) 580 s Post Ignition

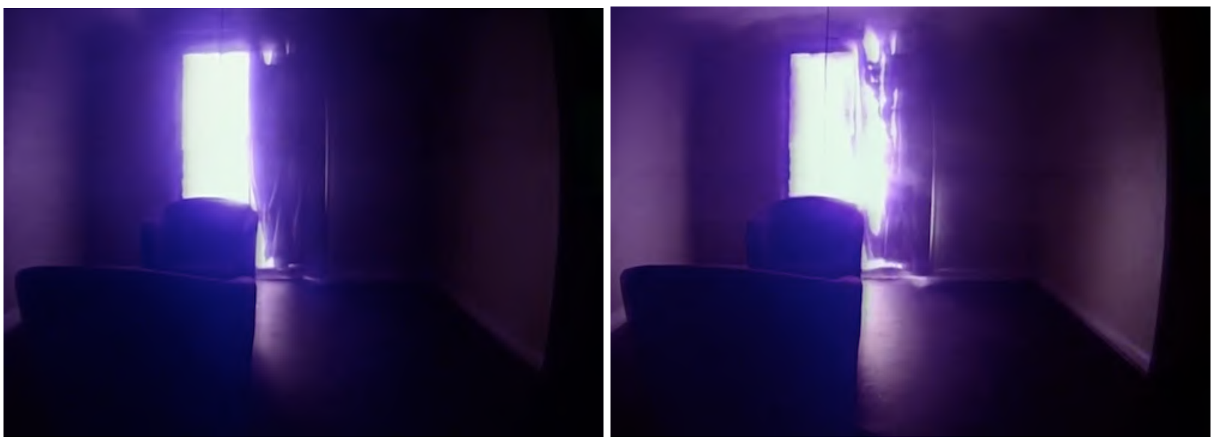
(f) 610 s Post Ignition

(g) 640 s Post Ignition

(h) 670 s Post Ignition

Figure 4.27: Flame spread from the lower-level apartment during Experiment 6.

Although the living room sliding glass door to Apartment C was closed prior to ignition, radiation from flames on the balcony was transmitted through the glass. The living room curtains on the interior side of the glass began to increase in temperature through absorption of radiant energy. As the curtain temperature continued to increase, they began to pyrolyze (i.e., undergo thermal decomposition that breaks down a solid to gas) approximately 625 s post-ignition (see Figure 4.28a). The curtains auto-ignited (i.e., the gases produced from pyrolysis reached their critical temperature such they spontaneously ignited without a direct source of ignition such as a flame) approximately 643 s post ignition (see Figure 4.28b). Flaming combustion in the apartment occurred before the living room sliding glass door failed 653 s after ignition (see Figures 4.28c and 4.28d).



(a) 625 s Post Ignition – Curtain Pyrolysis (b) 643 s Post Ignition – Curtain Combustion

(c) 653 s Post Ignition – Left Pane Failure (d) 653 s Post Ignition – Right Pane Failure

Figure 4.28: Ignition of the curtains in Apartment C prior to the sliding glass door breaking, and an interior view of the living room sliding glass door failing.

The time between ignition of the first-floor balcony and the failure of the sliding glass door was approximately 129 s (2:09). Once the sliding glass door failed, temperatures in the exposure apartment increased. Temperatures in the center of the Apartment C living room 5 ft and above increased in the 17 s after the sliding glass door failed to peaks ranging from 300 °F to 1035 °F. This was due to radiation from flames at the failed sliding glass door and from the smoke layer began to form in the apartment. Temperatures lower than 4 ft remained below 155 °F because those thermocouples were blocked from radiation by a chair located between the sensors and the flames. Exterior suppression then began 3 s after the failure of the sliding glass door, preventing further extension into Apartment C.

During the same period, smoke and flame from the extending exterior fire traveled up the rear of the structure and flowed into Apartment G via the open sliding glass door, steadily increasing temperatures at all elevations. At the time of exterior suppression, temperatures ranged from 185 °F to 1040 °F. The thermal conditions were not sufficient to cause ignition of the furnishings in the second-floor apartment due to the large volume above the fuels in the living room (recall that the second-floor living rooms had 11 ft peaked ceilings) and the short duration between temperature increase and the onset of suppression. Exterior suppression was initiated from side C and was effective as the primary suppression of the fire on all three floors of the structure with less than 500 gallons of water.

4.10 Interior Suppression vs. Exterior Fire Control

Scenarios 3 and 4 allowed for the comparison between interior suppression to exterior fire control for kitchen and living room fires on the first floor and second floor, respectively. The experiments were designed to produce similar fires to allow for comparisons between suppression tactics. The primary ignition in each experiment was in the kitchen, and the only open vent prior to ignition was half of the living room sliding glass door. Variations in the initial fire growth, however, resulted in differences in the thermal conditions within the apartments prior to suppression. The flow rate, nozzle, and hoseline were the same in all of the experiments: 160 gpm from a 7/8 in. smooth bore nozzle attached to 200 ft of 1 3/4 in. hoseline. Note: The differences in fire growth prior to suppression limit comparisons about the impact of each suppression tactic.

4.10.1 First-Floor Kitchen and Living Room Fire

Experiments 3A and 3B were ignited in the first-floor kitchen followed by a living room ignition. In both experiments, fire growth led to kitchen window failure, followed by firefighters manually venting the second-halves of the sliding glass doors. These events occurred earlier in Experiment 3B than in Experiment 3A, as summarized in Table 4.5. Additionally, drywall fell from the ceiling of the living room in Experiment 3A, which blocked the bottom half of the sliding glass door and limited air entrainment into the fire apartment. Despite firefighters eventually clearing the drywall, the size of the fire prior to the initial suppression action was smaller in Experiment 3A than in Experiment 3B. Figure 4.29 shows images comparing the conditions prior to the initial suppression action between each experiment.

Table 4.5: Comparison of Timing of Actions/Events Between Experiments 3A and 3B.

Action/Event	Experiment 3A Time [s (mm:ss)]	Experiment 3B Time [s (mm:ss)]
Ignition in kitchen	0 (00:00)	0 (00:00)
Ignition in living room	600 (10:00)	420 (07:00)
Kitchen window failed	709 (11:49)	522 (08:42)
Open sliding glass door blocked by fallen drywall	830 (13:50)	–
Vent other half of sliding glass door	969 (16:06)	589 (09:49)
Flashover in kitchen	–	632 (10:32)
Flashover in living room	–	714 (11:54)
Initial suppression action	1031 (17:11)	768 (12:48)

(a) Experiment 3A

(b) Experiment 3B

Figure 4.29: Images of conditions viewed from side A exterior immediately prior to the initial suppression actions in Experiments 3A and 3B.

The differences in thermal conditions between the experiments are seen in the temperature measurements in the respective fire apartments prior to suppression. The kitchen and living room in Experiment 3B transitioned to flashover, reaching peak temperatures above 1500 °F at all elevations. By the start of the initial water application, the kitchen temperatures ranged between 850 °F and 950 °F while the living room temperatures ranged between 1400 °F and 1700 °F. The fire in Experiment 3A did not reach flashover. Temperatures in the kitchen ranged between 630 °F–1600 °F, and the temperatures at all elevations in the living room remained below 1100 °F. Immediately prior to the initial suppression action, the living room temperatures ranged between 400 °F and 800 °F. Temperatures in the kitchen at that time ranged from 650 °F and 1060 °F.

In Experiment 3A, the suppression crew entered through the exterior breezeway door, opened the fire apartment door, and began flowing water with an interior suppression stream. Flames extended into the stairwell out of the top of the apartment door, causing peak temperature and velocity measurements at the door of 850 °F and 3.5 m/s (8 mph) at the 76 in. elevation, and

590 °F and 1 m/s (2 mph) at the 58 in. elevation. The temperatures above 3 ft on the first floor of the stairwell increased in response to the fire gases exhausting from the fire apartment. Peak temperatures ranged from 105 °F 4 ft above the floor to 520 °F, 1 in. below the ceiling. The buoyant, high-temperature combustion products filled the stairwell from the top down. A change in gas concentration was measured on the second floor of the stairwell, with worst-case conditions reaching of 19% O_2, 2.5% CO_2, and 0.4% CO (4000 ppm).

The suppression crew flowed water from the apartment entrance for 25 s, then advanced into the apartment with the nozzle open and flowing. The initial interior fire suppression flowed 180 gallons of water over 77 s to knock down the fire.

In Experiment 3B, the suppression crew first applied water from the exterior in four stages: 1) They swept the eave line above the kitchen window for 9 s; 2) directed the hose stream through the first-floor kitchen window for 10 s; 3) swept the hose stream across the second-floor balcony and eaves for 4 s; and 4) directed the hose stream through the living room sliding glass door at as steep an angle as possible for 11 s (hitting the living room ceiling and the lintel of the sliding glass door). The total time for flowing water during exterior water application was 37 s with a total of 94 gallons of water flowed. By the end of exterior water application, the temperatures in the kitchen and living room were below 800 °F and gas concentrations measured in the living room were improving.

The suppression crew then opened the exterior breezeway door and proceeded to the fire apartment door. The fire apartment door was opened and the suppression crew immediately began flowing water and advanced into the apartment. The time between the end of exterior water application and the start of interior suppression was 15 s. Gases exhausted out of the top of the open apartment door, but at lower temperatures and velocities than in Experiment 3A: 305 °F and 2 m/s (4 mph) at the 76 in. elevation, and 150 °F at the 58 in. elevation with gas flow fluctuating between ± 1 m/s (2 mph). The response in the stairwell to the combustion products exhausting from the fire apartment was also less than in Experiment 3A. The peak temperatures on the first floor ranged between 105 °F 5 ft above the floor and 185 °F 1 in. below the ceiling. Temperatures below 5 ft on the first floor did not increase above 90 °F. Gas concentrations measured on the second floor responded to the buoyant combustion products filling the stairwell from the top down, with worst-case conditions reaching 20.2% O_2, 0.9% CO_2, and 0.2% CO (2000 ppm).

During initial interior fire suppression 91 gallons of water were applied over 29 s. Combined with the exterior water application, total time flowing water was 81 s, resulting in 185 gallons of water flowed in Experiment 3B. Similar water flow time and quantity were used for interior suppression in Experiment 3A, at 77 s and 180 gallons.

Table 4.6 summarizes the key measurements comparing Experiment 3A to 3B. Reduced ventilation due to the fallen drywall limited the fire growth in Experiment 3A relative to Experiment 3B. Despite the difference in conditions at the start of suppression, both suppression tactics required similar amounts of time and water in each experiment. Furthermore, exterior water application in Experiment 3B reduced the hazard for entry to the fire apartment and in the stairwell relative to Experiment 3A.

Table 4.6: Summary of Key Measurements Comparing Experiment 3A to 3B.

Measurement	Experiment 3A	Experiment 3B
Fire Apartment Temperatures at Peak:		
Living Room	330 °F–1025 °F	1725 °F–2000 °F
Kitchen	630 °F–1600 °F	1500 °F–1575 °F
Fire Apartment Temperatures Immediately Prior To Initial Suppression Action:		
Living Room	370 °F–590 °F	1400 °F–1700 °F
Kitchen	650 °F–1060 °F	850 °F–950 °F
Peak Exhaust through Fire Apartment Door after Being Opened:		
76 in. Elevation	850 °F, 3.5 m/s (8 mph)	305 °F, 2 m/s (4 mph)
58 in. Elevation	590 °F, 1 m/s (2 mph)	150 °F, $\pm$ 1 m/s (2 mph)
Peak Gas Concentrations in Stairwell:		
Second Floor	19.0% O_2, 2.5% CO_2, 0.5% CO	20.2% O_2, 0.9% CO_2, 0.2% CO
Suppression:		
Water Used	180 gal	185 gal Exterior: 94 gal; Interior: 91 gal
Water Flow Time	77 s	81 s Exterior: 37 s; Interior: 29 s

4.10.2 Second-Floor Kitchen and Living Room Fire

Experiments 4A and 4B were both second-floor kitchen and living room fires. Both experiments were ignited in the kitchen, but Experiment 4B included an additional ignition location in the living room. The kitchen window in Experiment 4A began to fail during fire growth, which provided additional ventilation that resulted in an increase in temperature near the kitchen ceiling. However, the majority of the window remained intact until firefighter intervention. To avoid similar ambiguity about the vent size and timing, the kitchen window in Experiment 4B was vented manually. Sufficient ventilation was present for the living room to reach flashover, which was not achieved in Experiment 4A. The timing of these events are summarized in Table 4.7. The result of these differences in initial configuration and fire growth was a larger fire in Experiment 4B than in Experiment 4A. Figure 4.30 shows images comparing the side A exterior conditions prior to the initial suppression action between each experiment.

Table 4.7: Comparison of Timing of Actions/Events Between Experiments 4A and 4B.

Action/Event	Time [s (mm:ss)]	
	Experiment 4A	Experiment 4B
Ignition in kitchen	0 (00:00)	0 (00:00)
Ignition in living room	–	0 (00:00)
Vent kitchen window	–	451 (07:31)
Flashover in living room	–	530 (08:50)
Initial suppression action	817 (13:37)	541 (09:01)

(a) Experiment 4A

(b) Experiment 4B

Figure 4.30: Images of conditions viewed from side A exterior immediately prior to the initial suppression actions in Experiments 4A and 4B.

Flashover occurred in the living room during Experiment 4B shortly before the initial suppression action, as temperatures ranged between 1200 °F and 1600 °F. Temperatures in the kitchen reached peaks at the same time, ranging between 475 °F 1 ft above the floor and 920 °F 1 in. below the ceiling. Temperatures were lower in Experiment 4A, reaching peaks in the kitchen between 750 °F 1 ft above the floor and 1600 °F 1 ft below the ceiling and peaks in the living room between 180 °F 1 ft above the floor and 900 °F 1 ft below the ceiling. About 3 min before the initial suppression action, the thermocouple array in the kitchen fell due to damage to the ceiling drywall. Before the sensors fell, the kitchen temperatures ranged from 295 °F 1 ft above the floor to 1600 °F 1 in. below the ceiling. Immediately prior to the initial suppression action, the living room temperatures ranged from 135 °F 1 ft above the floor to 590 °F 1 ft below the ceiling.

In Experiment 4A, the suppression crew entered through the exterior breezeway door, opened the fire apartment door, and began flowing water using an interior suppression stream. Smoke exhausted into the stairwell out of the top of the apartment door, causing peak temperature and velocity measurements at the door of 290 °F and 1.5 m/s (3 mph) at the 76 in. elevation, and 110 °F and 1 m/s (2 mph) at the 58 in. elevation. The temperatures above 3 ft on the second floor of the stairwell increased in response to the fire gases exhausting from the fire apartment. Peak temperatures ranged from 110 °F 4 ft above the floor to 215 °F 1 in. below the ceiling. Smoke filling the stairwell also affected the second-floor gas concentrations, with worst-case conditions reaching 18.0% O_2, 4.8% CO_2, and 0.5% CO (5000 ppm).

The suppression crew flowed 184 gallons of water over 76 s to knock down the fire. The fire had spread to the attic space due to the drywall failure that was unique to this experiment. Further overhaul operations were required and those corresponding water flows were not considered for this assessment.

In Experiment 4B, the first suppression action was sweeping the eave line above the living room sliding door for 8 s using exterior fire control. The nozzle firefighter then directed the hose stream at the sliding glass door lintel for another 8 s to disperse water in the living room. The total time for exterior water application was 16 s, resulting in 45 gallons of water flowed. By the end of exterior water application, the temperatures in the kitchen and living room were below 1000 °F and gas concentrations measured in the living room were improving.

The suppression crew then opened the exterior breezeway door and proceeded to the fire apartment door. The fire apartment door was opened and the suppression crew immediately began flowing water and advanced into the apartment. The time between the end of exterior water application and the start of interior suppression was 29 s. Gases exhausted out of the top of the open apartment door at lower, but similar temperatures and velocities as in Experiment 4A: 230 °F and 1.5 m/s (3 mph) at the 76 in. elevation, and 105 °F at the 58 in. elevation, with flow initially into the apartment at 1 m/s (2 mph) before slowing to 0 m/s. The response in the stairwell to the combustion products exhausting from the fire apartment was also less than in Experiment 4A. The peak temperatures on the second floor ranged between 115 °F 5 ft above the floor and 225 °F 1 in. below the ceiling. Temperatures below 5 ft on the second floor did not noticeably increase. The smoke layer did not descend low enough to affect gas concentration measurements on the second floor (sampled 4 ft above the floor).

Interior suppression in Experiment 4B required 95 gallons of water over a duration of 42 s. Combined with the exterior water application, total time flowing water was 58 s, resulting in 140 gallons of water flowed in Experiment 4B, which was greater than the interior suppression streams in Experiment 4A (184 gallons over 76 seconds)

Table 4.6 summarizes the key measurements comparing Experiment 4A to 4B. Similar to Scenario 3, differences in the initial configuration and fire growth produced dissimilar fires, thereby limiting conclusive comparisons between suppression tactics.

In both scenarios, however, the fire extinguished using interior suppression (Experiments 3A and 4A) had less severe thermal conditions prior to the start of suppression compared to the experiments using exterior fire control (Experiments 3B and 4B). Comparisons between the responses to each suppression tactic yielded consistent trends in both scenarios: exterior fire control (Experiments 3B and 4B) reduced the hazard for entry to the fire apartment and in the stairwell relative to interior suppression (Experiments 3A and 4A).

Table 4.8: Summary of Key Measurements Comparing Experiment 4A to 4B.

Measurement	Experiment 4A	Experiment 4B
Fire Apartment Temperatures at Peak:		
Living Room	180 °F–900 °F	1200 °F–1600 °F
Kitchen	750 °F–1600 °F	475 °F–920 °F
Fire Apartment Temperatures Immediately Prior To Initial Suppression Action:		
Living Room	135 °F–510 °F	1225 °F–1600 °F
Kitchen	—	450 °F–900 °F
Peak Exhaust through Fire Apartment Door after Being Opened:		
76 in. Elevation	290 °F, 1.5 m/s (3 mph)	230 °F, 1.5 m/s (3 mph)
58 in. Elevation	110 °F, ± 1 m/s (2 mph)	105 °F, 0 m/s
Peak Gas Concentrations in Stairwell:		
Second Floor	18.0% O_2, 4.8% CO_2, 0.5% CO	20.8% O_2, 0.1% CO_2, 0% CO
Suppression:		
Water Used	184 gal	140 gal Exterior: 45 gal; Interior: 95 gal
Water Flow Time	76 s	58 s Exterior: 16 s; Interior: 42 s

5 Tactical Considerations

A tactical consideration is defined as "an evidence-based concept for the fire service to consider implementing to enhance efficiency and effectiveness, and to increase knowledge to accomplish their mission [39]." The following considerations are meant to inform and further educate the fire service. They are recommendations from research that provide information to the fire service allowing firefighters to determine how, what, and when to utilize as it relates to their department and response model. Tactical considerations are not policy and are not specifications on how to enact or carry out a specific tactic.

5.1 Evaluation of Previous Research Findings in Acquired Structures

Previous research conducted by UL FSRI included concepts related to suppression methods both interior and exterior as well as horizontal, vertical, and positive pressure ventilation. The previous research was conducted in purpose built one- and two-story structures that resembled single family homes along with acquired structures across the United States. All experiments were conducted in a laboratory setting, under controlled conditions with hardened structures to withstand multiple burns without losing structural integrity. Other research was conducted in acquired structures that incorporated fire spread to the structure, beyond the contents. This study aims to determine if and how previously published tactical considerations developed from these experiments apply to similar experiments conducted in acquired multi-family dwellings.

5.1.1 Survivable Spaces on Arrival

A previously published tactical consideration titled *There Can Be Survivable Spaces on Arrival at a Single Family Residential Home* describes the complexities behind anticipating the locations of survivable space within a residential fire. As stated in the report, the survivability of an occupant is dependent on their exposure to heat and toxic gases, their proximity to the fire location, and their elevation within the space [7]. Thermal exposure is greater nearest the fire, and toxic exposure is greatest at higher elevations. Additionally, it was shown that an occupant located in a bedroom with a closed door had a greater chance of survival than an occupant located in a bedroom with an open door.

Each experiment in this series had instrumentation to monitor gas concentrations (oxygen, carbon dioxide, and carbon monoxide) at 4 ft above the floor in the lower-level stairwell, first-floor stairwell, and the second-floor stairwell. Eleven of the 13 experiments measured gas concentrations within the fire apartment, while the remaining two experiments measured gas concentrations in an exposure apartment. The gas concentrations measured were used to calculate a toxic FED to assess the tenability of potential occupants.

In the 11 experiments in which gas measurements were made in the fire apartment, six had an FED below 0.3, the level considered to be the incapacitation dose for the most susceptible population groups, at the time the exterior door was opened, which indicated the arrival of the fire department (Table 5.1).

Table 5.1: Occupant Exposures in Living Room Prior to Firefighter Intervention

Exp #	Fire Location	Ventilation	FED at Exterior Door Open
1A	Lower-Level Bedroom	None	17
1B	Lower-Level Bedroom	Apartment Door	2.4
1C	First-Floor Bedroom	Bedroom Window	0.13
1D	First-Floor Bedroom	Bedroom Window	0.05
1E	First-Floor Bedroom	Bedroom Window	0.01^{+}
2A	First-Floor Bedroom	Bedroom Window	0.23
2B	First-Floor Bedroom	Bedroom Window	0.17
3A	First-Floor Living Room & Kitchen	Kitchen Window & Sliding Glass Door	1.6
3B	First-Floor Living Room & Kitchen	Kitchen Window & Sliding Glass Door	12
4A	Second-Floor Kitchen	Sliding Glass Door	$< 0.01^{*}$
4B	Second-Floor Living Room & Kitchen	Kitchen Window & Sliding Glass Door	12

$^{+}$ Bedroom door closed during experiment
* Ceiling failure during second floor kitchen fire

Consideration should be given to the potential for survivable spaces in the fire apartment upon arrival. The spread of FED values (≈0–17) at exterior door open indicates the challenge to assuming a space may or may not be survivable because tenability depends on a number of factors, such as the ventilation configuration and fire progression on arrival. Table 5.1 demonstrates the impact of the ventilation configuration on the living room FED, particularly when the living room was part of the flow path which drove the FEDs higher. The open apartment door in Experiment 1B established a flow path from the bedroom fire through the apartment to the stairwell. In Experiments 3A, 3B, and 4B, the open sliding glass door established a flow path where combustion gases flowed through the living room and out of the open living room sliding glass door, which ultimately led to higher potential exposures.

Table 5.1 also demonstrates that locations not part of the flow path remained tenable for longer periods of time. Experiments 1C, 1D, 1E, 2A, and 2B were bedroom fires where the bedroom window was vented prior to ignition or prior to suppression. This ventilation action established a flow path with an intake and exhaust at the window. While this vent limited smoke flow into the kitchen and living room, bedroom conditions were more hazardous compared to the bedroom experiments that were not vented. As a result, it important to consider the impact that ventilation tactics have throughout an entire occupied space.

In addition, unknown factors can effect fire growth and the resulting smoke and heat spread, such as those that occurred in Experiments 1E and 4B. Experiment 1E was a first-floor bedroom fire in which the door to the bedroom closed due to pressure buildup in the apartment 215 s after ignition. The closed door isolated the fire room from the remainder of the apartment, which limited the smoke transport (see Figure 5.1a). As a result, the FED remained low. Experiment 4A was second-floor kitchen fire. Prior to fire department arrival, a portion of the kitchen ceiling failed, which allowed smoke to flow into the attic space. The failure, combined with the 11 ft living room ceiling, led to a smoke layer that remained above the 4 ft elevation for the duration of the experiment (see Figure 5.1b). As a result, the FED remained negligible for the duration of the experiment.

(a) Experiment 1C Living Room

(b) Experiment 4A Living Room

Figure 5.1: Examples of survivable space prior to firefighter intervention for Experiments 1C and 4A. Both camera views are from the living room, at floor level.

Upon firefighter intervention, it is important to recognize that opening the apartment door was ventilation. The open door established a new flow path through the apartment similar to Experiment 1B, which could increase the exposure to potential occupants. Also, recall Section 4.7, which emphasized that the FED will continue to increase even after the onset of suppression as long as combustion products or occupants remain in the apartment.

The two experiments where gas concentrations were measured in an exposure unit were designed to examine fire spread through multiple units with the apartment building. Experiment 5 was conducted with a lower-level fire with the fire apartment door open to examine how heat and toxic gases spread throughout the stairwell and into second-floor exposure apartments. The door to one of the exposure units was closed at 341 s post-ignition while the other unit remained open for the duration of the experiment. In the open exposure, additional ventilation in the form of opening the living room sliding glass door was provided 417 s post-ignition. Figure 5.2a shows the side A conditions at the time of firefighter entry, 687 s post-ignition. At the time of entry, temperatures at the second-floor landing ranged between 650 °F and 800 °F. The FED in the open unit was 344 (three orders of magnitude higher than the FED for incapacitation for the median of susceptible populations), and living room temperatures ranged between 300 °F and 675 °F. Although gas measurements were not made in the closed-door exposure, temperatures did not exceed 85 °F, and there was minimal smoke layer development.

Experiment 6 was conducted in a lower-level apartment to study exterior fire propagation (i.e., fire spread vertically from balcony to balcony). In this experiment, the first-floor living room sliding glass door was closed from the start of the experiment, while the second-floor living room sliding glass door was left open. Figure 5.2b shows the exterior conditions on side C 15 s prior to exterior water application just as the sliding glass door on the first-floor balcony began to show signs of failure. At the time of suppression, both exposures had high living room ceiling temperatures as smoke began to fill the apartments, but temperatures near the floor remained at or below 150 °F. Gas concentrations were only measured on the second floor, and the FED remained negligible at the time of suppression.

(a) Experiment 5 - 687 s Post Ignition

(b) Experiment 6 - 640 s Post Ignition

Figure 5.2: Examples of exterior conditions prior to intervention in experiments with survivable spaces in exposure units.

Multi-family dwellings typically have the potential for a higher life-hazard compared to a single-family dwelling due to the higher occupant concentration. Although an enclosed stairwell will likely capture most smoke that enters from a fire apartment, exposure apartments and the stairwell (especially areas below the fire floor) should be considered survivable space until searched or declared otherwise by responding firefighters. Even with fire extension to the exposure apartments either from the interior enclosed stairwell or exterior via auto-extension up the building facade, survivable spaces may be present in the apartments due to closed doors or occupants remaining/hiding low in the space.

5.1.2 Water Usage in Residential Fires

Tactical considerations developed from prior UL FSRI-led full-scale experiments stress that applying water in the most efficient manner, including both interior suppression and exterior fire control, results in decreased temperatures, heat release rates, and fire gas production [7, 9].

For the experiments in the laboratory, "Study of the Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival," suppression was achieved with less than 250 gal of water for 23 of the 24 experiments conducted in the one-story single family residential structure. The peak usage was 257 gal. Suppression techniques included either a shutdown-and-move or a flow-and-move method for interior suppression, and a straight stream pattern at a steep angle off the fire room ceiling for exterior fire control. Average water flowed during the fire attack experiments for initial knock down is listed in Table 5.2, organized by suppression and ventilation configuration.

Table 5.2: Average Total Water Flowed for Suppression in Fire Attack Experiments [7]

Suppression Tactic	Fire	Ventilation Openings*	Water Usage (gal)
Interior Suppression	One Room	None	83 ± 24
Interior Suppression	One Room	One Window	91 ± 30
Interior Suppression	Two Rooms	Two Windows	191 ± 43
Exterior Fire Control	One Room	One Window	62 ± 30
Exterior Fire Control	Two Rooms	Two Windows	120 ± 42

* Additional ventilation included the open front door for interior suppression operations.

For the acquired structure single family experiments conducted as part of the "Study of Coordinated Attack Utilizing Acquired Structure," similar results were found. The single-family dwelling experiments utilized structures that provided more realism when compared to the purpose-built laboratory structures. These acquired structures allowed for fire extension beyond the contents and into the structure both from the interior and exterior. Resulting average water flows are listed in Table 5.3. The total water usage was in line with the values reported from the fire attack study. Primary extinguishment in all 20 experiments was achieved with less than 250 gal, with a peak of 243 gal.

Table 5.3: Average Total Water Flowed for Suppression in Single-Family Experiments [9]

Suppression Tactic	Fire	Ventilation Tactic*	Water Usage (gal)
Interior Suppression	Second-Floor Bedroom	Post Fire Control	129 ± 36
Interior Suppression	Second-Floor Bedroom	Prior to Fire Control	121 ± 10
Exterior Fire Control	Second-Floor Bedroom	Post Initial Water Flow	147 ± 32
Exterior Fire Control	Second-Floor Bedroom	Failed Ceiling	219 ± 24
Interior Suppression	First-Floor Kitchen	Prior to Fire Control	139 ± 56
Exterior Fire Control	First-Floor Kitchen	Post Initial Water Flow	95 ± 56

* Two windows in each fire room were removed prior to ignition and additional ventilation included the open front door for interior suppression operations.

Similar amounts of water were used to suppress fires in these multi-family dwellings. During 12 of the 13 experiments, a single 1 3/4 in. hoseline with either a combination nozzle flowing 150 gpm at 50 psi or a 7/8 in. smooth bore nozzle flowing 160 gpm at 50 psi was utilized for initial knock down and suppression. Figure 5.3 shows the total water flowed during each experiment.

During Experiment 1A, a pressurized water extinguisher was utilized for final suppression because the fire had nearly self extinguished prior to fire department entry into the building. Although a single 1 3/4 in. hoseline was used to extinguish the fire in Experiment 1B, a sensor error resulted in no flow data recorded. The data presented below is an estimate of the gallons used for suppression based off the duration of audible queues recorded on personal video recording devices placed on each firefighter during experimentation.

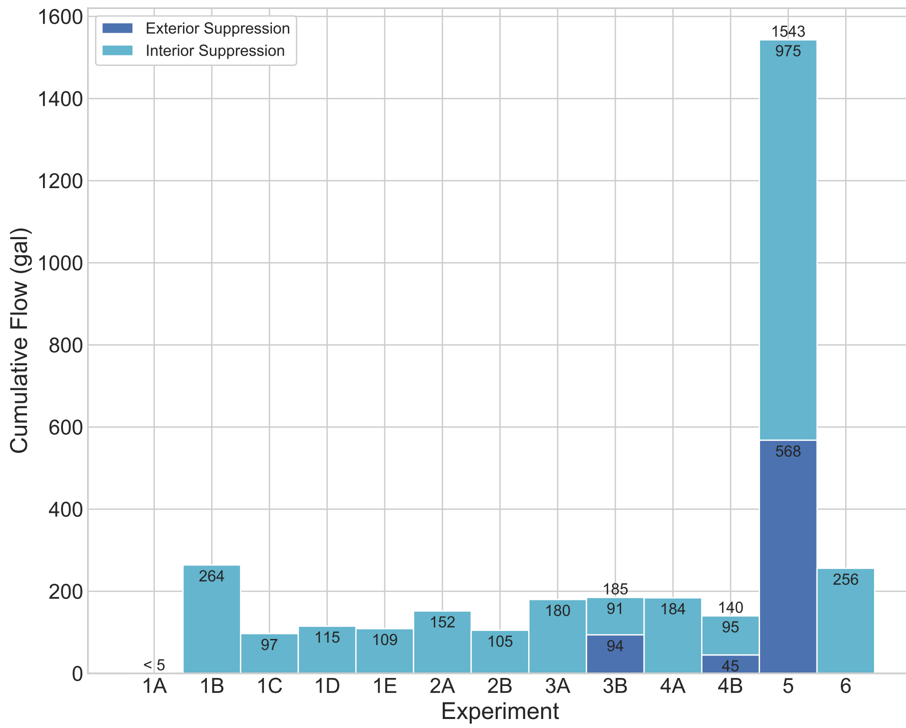


Figure 5.3: Estimated total water flowed for primary suppression during each experiment.

Experiments involving a single room of fire (Experiments 1B–2B) on average required 139 ± 54 gal of water for initial knock-down and suppression, while experiments involving multiple rooms of fire (Experiments 3A–4B) were suppressed with an average of 172 ± 19 gal of water. Both interior suppression and exterior fire control techniques were employed for extinguishment in the multiple rooms of fire experiments. The average amount of water used for interior suppression (Experiments 3A and 4A) was 182 ± 4 gal compared to 162 ± 22 gal for exterior fire control (Experiments 3B and 4B). The water flowed for suppression in multi-family dwellings was comparable to the water flowed for two rooms of fire in the fire attack study and single-room fires in the single family dwelling fires for the coordinated fire attack study. Although this water flow data does not include the water used during overhaul and mop-up operations, the primary suppression streams used in both single and multiple rooms of fire employing either interior suppression or an exterior fire control technique required total flow that could be attained with less than the 300 gal minimum booster tank capacity on fire apparatus [40].

The most water used for suppression of a room and contents fire was Experiment 1B. Flow data was not recorded, so the number presented above may be a conservative overestimate. During Experiment 1B, the suppression crew flowed water while advancing into the apartment, but due to limited visibility, the duration of the first two flows (9 s and 17 s) were conducted while advancing through the living room. The third flow (which lasted 27 s) was conducted while inside the kitchen, and the fourth flow (which lasted 46 s,) was conducted inside the fire room (bedroom). Fire room temperatures did not decrease from suppression efforts until 768 s post ignition, corresponding with the fourth flow. The first three flows did not get water on the burning fuel and had limited impact on thebedroom fire. If only the fourth flow of 46 s is considered, the total water flowed for suppression would be approximately 123 gal. Although this value is more in line with other experiments and provides context to the similar nature of fire sizes and effectiveness of water as a suppression agent, the total water flow is equally important. With limited visibility, it may not always be clear where in the space the primary fire is, and it should be expected that water flow will occur that may not immediately impact the fire source. It is also important to note that the first three flows were effective in cooling the gases in the living room and kitchen as the crew advanced to the bedroom.

Fires that spread between multiple apartments or multiple balconies highlight the tactical considerations from previous research, specifically regarding the importance of getting water where it is needed. These experiments required more water for suppression than experiments designed to result in one or two rooms of fire (Experiments 5 and 6). The amount of water used for suppression in Experiments 5 and 6 reinforce the tactical considerations from previous research. During Experiment 5, interior suppression lasted approximately 443 s (flowing 975 gal of water) but was unable to get water to the fuel located in the fire apartment. The hose stream was only able to reach what was in the line of sight in the stairwell. The water flow decreased stairwell temperatures enough to make entry into the structure but was not able to suppress the fire, preventing firefighters from advancing to the lower level.

Exterior water flow lasted approximately 227 s, flowing 568 gal of water in separate exterior applications through the sliding glass door of Apartment J (fire apartment). The first flow was 86 s in duration and flowed approximately 215 gal of water, and the second flow was 141 s in duration and flowed approximately 353 gal of water. The hose stream was directed toward the exterior balconies during the first flow and resulted in a visual knock-down of the fire in 12 s. Temperatures in the fire apartment and stairwell subsequently decreased. This allowed the interior suppression crew to advance further into the structure and down the lower-level stairs. The exterior fire control crew repositioned for the second exterior flow, which was directed into the fire apartment at a steeper angle and was effective in further wetting the fuel in the fire apartment. Concurrent to the second exterior flow, the interior suppression crew advanced through the fire apartment door and began flowing water into the fire apartment, further decreasing fire room temperatures.

So, exterior fire control was the most efficient way to get water onto the seat of the fire. Interior suppression was initially ineffective at getting water onto the seat of the fire. This resulted in a large flow that did not decrease temperatures to a level below the potential for thermal damage to gear and potential injury, which prevented further firefighter advancement into the structure. This was an example of water being applied in an area other than the fire compartment with limited impact on the overall conditions within the structure. It is important to note that during this experiment, the interior and exterior flows occurred simultaneously without adverse conditions being reported from the interior crew.

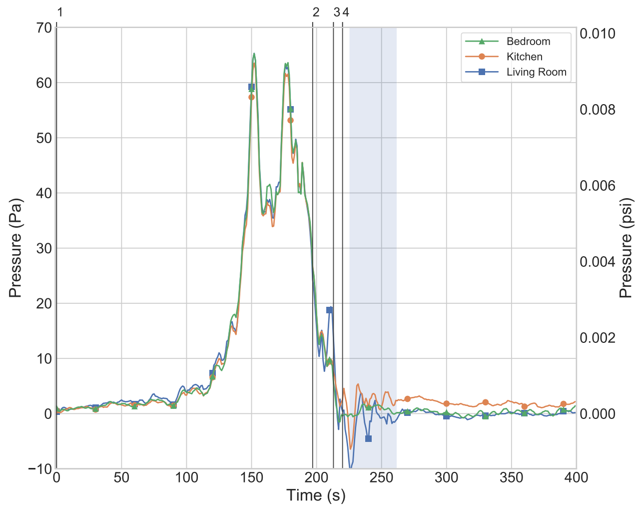
During Experiment 6, three floors of exterior fire resulted from a single room and contents fire in the living room of the lower-level Apartment I. Prior to suppression, an exterior fire spread upward, igniting the first- and second-floor balconies. This also spread fire into both exposure apartments (Apartments C and G), and to the eaveline. Exterior water flow lasted for approximately 129 s, flowing 256 gal of water in two separate exterior flows. The first flow (69 s long) extinguished the three-story high flames on the exterior of the structure, while the second flow (60 s long) suppressed the apartment fire on the first floor. The water flowed to suppress exterior fire was 136 gal, while the water flowed to suppress interior fire was 120 gal. The total water flowed to extinguish exterior and interior fire was comparable to the dual room and contents fires presented in the fire attack study and the single room and contents fire presented in this report. Exterior fire required exterior water because it was able to be directly applied to the seat of the fire in the most effective means possible.

5.1.3 Impact of Gas Contraction

The introduction of cool water into a fire compartment that has transitioned through flashover with floor to ceiling temperatures above 1100 °F rapidly cools the walls, ceiling, and solid fuels, along with gaseous fuels generated by the fire. A temperature change from above 1100 °F to below 300 °F with effective suppression will result in gas contraction in the fire compartment and adjacent spaces, as seen in the fire attack study. The fire attack study includes discussion on the topic of steam expansion and gas contraction, which states:

> "During fire suppression, the conceptual effects of steam expansion are not seen when water is applied to a flashed-over compartment with gypsum walls. The transfer of energy causes the gases to cool rapidly, which causes them to contract. The gases contract more than [converting to steam] expands; in the end, the net effect is contraction [7]."

Experiment 1C pressures are shown in Figure 5.4. As the fire grew, pressures rose until the fire transitioned to ventilation-limited conditions in the apartment. Once the bedroom window was ventilated, pressure was released and returned to ambient. At the start of suppression, and simultaneous with the rapid decrease in temperatures, the pressures in the kitchen and living room of the fire apartment dropped below 0 Pa, reaching -6.0 and -10.8 Pa respectively. This was likely due to gas contraction, as surface and gas cooling occurred on the approach to the fire compartment.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

Figure 5.4: Fire apartment pressures for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

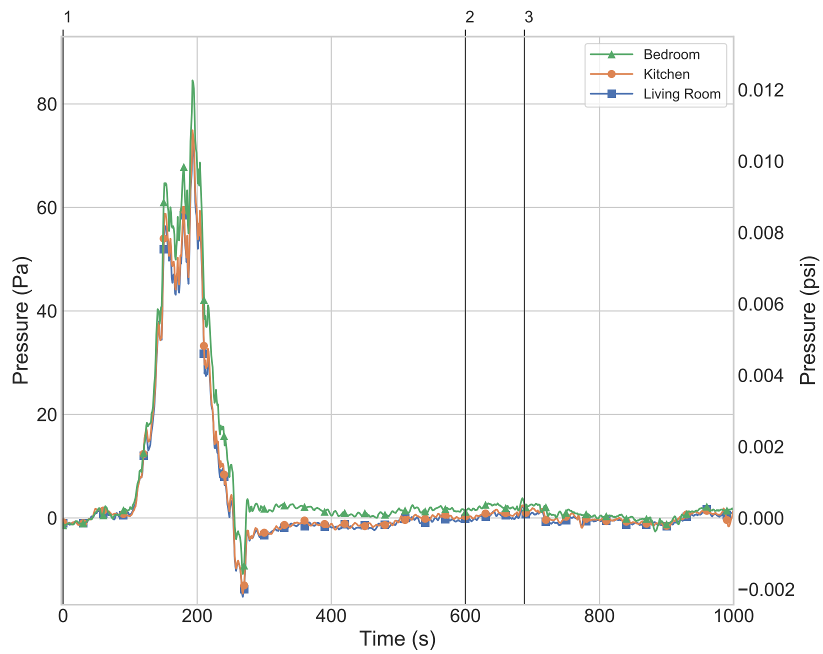
Figure 5.5 shows two exterior camera view stills of the bedroom (fire room) window as it was being vented and right at the start of suppression during maximum cooling for Experiment 1D. Experiment 1D was chosen to show this phenomenon because it had the best unobstructed camera view of the window opening. As the window was being vented, the introduction of fresh air allowed the fire gases to ignite and flames were then present at the window opening extending out and up. The neutral plane was approximately one third of the way up from the bottom sill, indicating bi-directional flow with fresh air being entrained low (see Figure 5.5a). At the onset of suppression, as the largest temperature drop occurred while surfaces were instantaneously cooled, the fire gases also cooled and contracted. Figure 5.5b shows gases being drawn back into the fire compartment during the initial cooling effort from interior suppression.

(a) Experiment 1D During Vent

(b) Experiment 1D at Start of Suppression

Figure 5.5: Example of gas contraction during initial rapid cooling of the fire compartment in Experiment 1D.

It should also be noted that gas contraction can occur independent of firefighter intervention. In Experiment 1A, the fire apartment had no ventilation opening beyond natural leakage. As the fire grew and spread to other fuels in the bedroom of the fire apartment, temperatures and pressures in the bedroom, kitchen, and living room rose. Smoke filled the apartment and a smoke layer descended. Oxygen concentrations simultaneously decreased. As the fire consumed the available oxygen in the compartment, combustion became unsustainable. The self-extinguishment of the fire led to a decrease in temperature. The temperature drop led to gas contraction, which correspondingly resulted in a drop in pressure to below ambient levels. Given that higher pressure always flows toward an area of lower pressure, air entered the apartment through cracks and crevices until the pressures equalized, though not enough air was supplied to prevent the fire from continued decay. See Figure 5.6 for the fire apartment pressures.



	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	600
3	Open apartment door	688

Figure 5.6: Fire apartment pressures for Experiment 1A. Each pressure tap was installed 4 ft above the floor.

Increasing the amount of total water flowed onto burning surfaces inside a fire compartment (including the walls, floor and ceiling) will increase the rate at which temperatures decrease, and correspondingly the amount of gas contraction. Utilizing a straight stream or smooth bore nozzle and appropriately cooling the surfaces (as shown in previous research [5, 7, 9]) will lead to the quickest and most effective means of suppression. Temperature and pressure decreases were not just localized to the fire room but were seen throughout the apartment, which improved conditions in all areas.

5.1.4 Water Flow Can Impact The Flow of Gases

A flow path is the route followed by smoke, air, heat, or flame toward or away from an opening, typically a window, door, or other leakage point, due to differences in pressure. In a flow path, fresh air is entrained toward the fire (i.e., lower pressure intake) and buoyant fire gases are exhausted (i.e., higher pressure exhaust). The intake and exhaust can be at the same vent, leading to bi-directional flow at the vent, or they can exist at separate vents, leading to unidirectional flow at the respective vents. During suppression, air entrainment from a hoseline can impact the flow of gases within the structure. As stated in the previous tactical consideration *Water Flow Can Impact The Flow Path* from the fire attack study:

> "During an interior attack, applying water down the hallway without a vent opposite is a method in which entrained air can alter the flow path such that the hot gases are

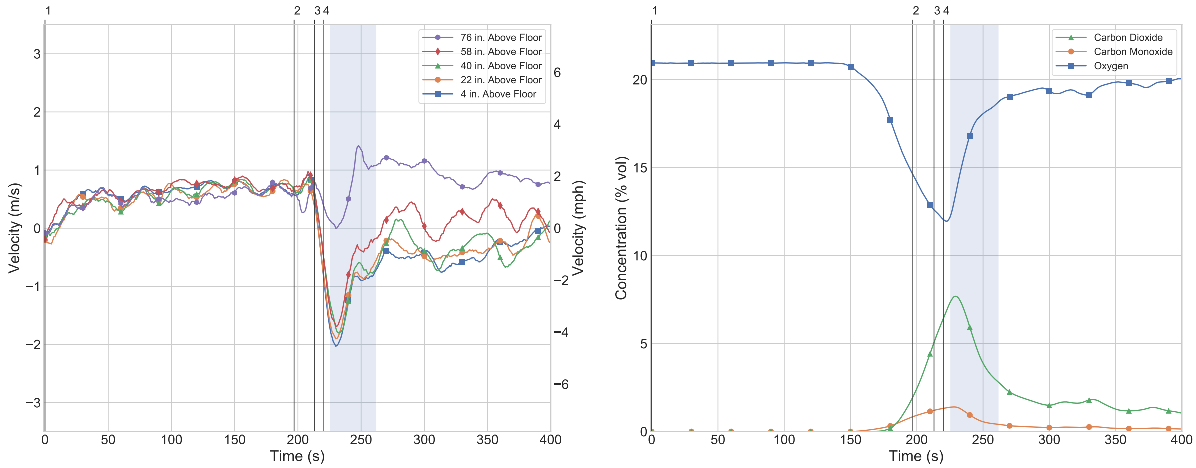
> no longer flowing over the heads of firefighters as they advance. [...] When advancing during an interior attack with a vent opposite, the entrainment was not only capable of stopping flow at the hallway, it was capable of re-directing the flow ahead of the advancing suppression crew [7]."

This consideration suggests air entrainment from a manipulated hose stream can be used to your advantage during interior advancement and suppression and during post-suppression ventilation (e.g., hydraulic ventilation).

During the fire attack study, the suppression crew advanced down a narrow hallway that connected the bedrooms to the rest of the structure while flowing-and-moving until the crew was past the threshold to the fire compartment. Water was then directed onto the base fuels. The flow-and-move advancement technique utilized an O pattern, and was able to occlude the hallway due to the air entrainment and gas contraction. The reversal of the hot gas flow was driven by a 160 gpm flow, and the resulting air movement caused the gas flow in the hallway to become unidirectional toward the bedroom (fire room) at the end of the hall. With the bedroom window vented ahead of the suppression crew and the front door open behind, the gas flow was unidirectional from the front door, down the hallway, and out of the bedroom window. This technique created a less hazardous environment for the advancing crew and improved victim survivability behind the operating hoseline as fire gases were now redirected through the fire room and out of the structure.

Similar trends were seen in the multi-family experiments where the suppression crew was able to impact the flow of gases between the open apartment door and the bedroom (fire room). Two first-floor bedroom fires incorporated fire room window ventilation within 10 s prior to suppression. Two other experiments began with the fire room window open from ignition. In all four experiments, there was a ventilation opening ahead of the suppression crew as they advanced on the interior of the structure. In each experiment, the suppression crew immediately began flowing water as the fire apartment door was opened. This approach minimized the time between adding a ventilation opening (i.e., opening the door) and leveraging the air entrainment, gas cooling, and gas contraction effects (see Tactical Consideration 5.1.3) from the water flow to limit the spread of gases.

As the suppression crew began to flow water and move toward the fire room, fresh air was entrained from the stairwell. Apartment door velocities below 76 in. during the time of suppression ranged between -1.0 m/s (2.2 mph) and -2.0 m/s (4.5 mph), indicating flow into the apartment due to a combination of gas contraction from cooling and entrainment from the hose stream (see Figure 5.7a). Should the apartment door have been opened without the coordinated suppression efforts, bi-directional flow would have been present with buoyant gases exhausted high and air entrained low as seen in Experiment 1B, where the apartment door was open prior to ignition. In Experiment 1B, flows above 48 in. were outflow. Due to the operating hose stream, the redirected gases were able to exhaust through the fire room and out of the bedroom window. The fresh air entrained into the apartment, combined with cooling due to suppression, aided in the rapid return of gas concentrations toward ambient levels as shown in Figure 5.7b.



(a) Apartment Door Velocities (b) Gas Concentrations

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

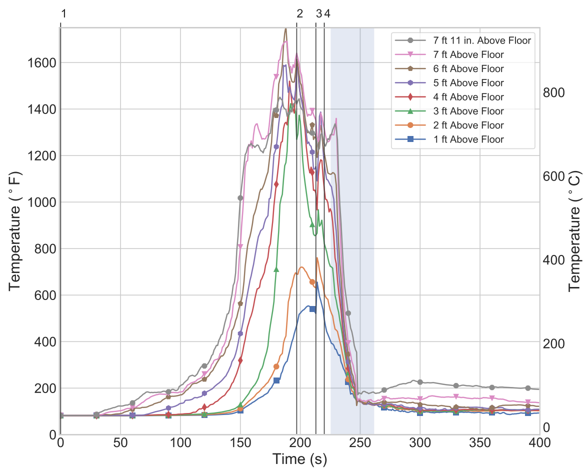
Figure 5.7: Fire apartment door velocities and gas concentrations for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

As firefighters operate within the flow path on the approach to a fire compartment(s), consideration should be given to an approach which takes advantage of maximum surface cooling (and subsequent gas contraction), hot gas flow reversal, and entrainment of air behind the suppression crew. This ability of a flowing hose stream to impact the flow of gases was seen throughout the multi-family dwelling experiments. This was similar to results presented in the fire attack study, because a similar advancement method was utilized in that study.

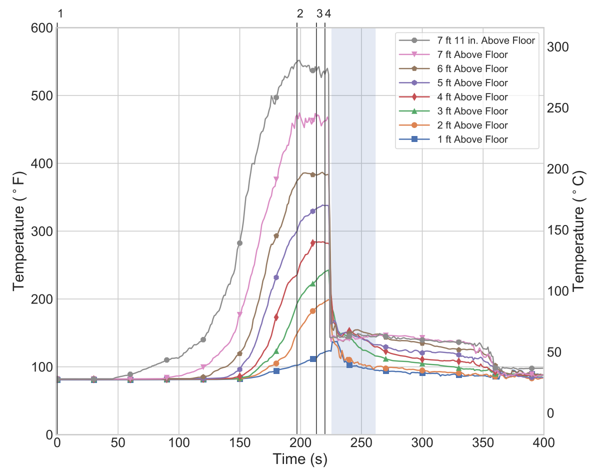
5.1.5 Cool While Advancing

In a related manner, the fire attack study also highlighted the importance of keeping the nozzle open and flowing during interior advancement to not only control the space and cool surfaces, but also to protect firefighters on their approach to the fire compartment(s) [7]. Operating in an exhaust portion of a flow path on the way to the fire compartment(s) places firefighters in the highest thermal threat as the fire gases are exhausting toward and past the advancing crew.

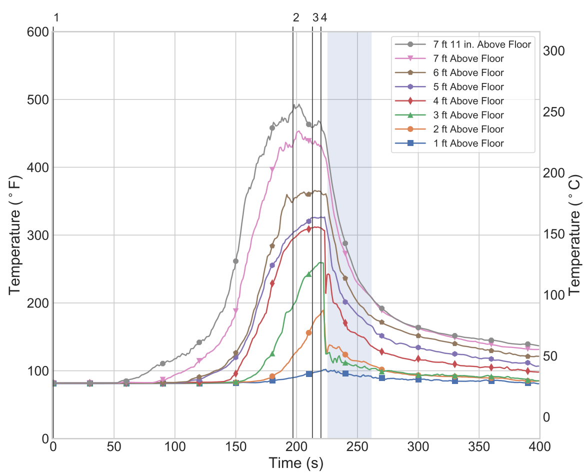
The ability of a flowing hoseline to impact gas flow within a flow path offers numerous advantages, including surface cooling, occlusion of gases exiting into the common stairwell, reversal of gases toward an exterior vent, and entrainment of fresh air. These principles were seen throughout the multi-family dwelling experiments where all interior attacks utilized a flow-and-move approach with an O pattern. An additional benefit of cooling as you advance includes reducing the thermal hazard for the firefighters engaged in suppression and others operating in the area of the fire. Examining the temperatures in the apartment for Experiment 1C show the hazard beyond the bedroom (fire room) into the rest of the apartment, as seen in Figure 5.8.



(a) Bedroom



(b) Kitchen



(c) Living Room

	Action/Event	Time (s)
1	Ignition	0
2	Open exterior door	197
3	Ventilate bedroom window	213
4	Open apartment door; flow-and-move to fire room	220

Figure 5.8: Bedroom, kitchen, and living room temperatures for Experiment 1C. Blue shaded regions indicate time and duration of water flow.

To fully understand the context of the temperature data presented, one must remember the location of the thermocouple measurements in the fire apartment. See Figure 5.9 for an example of what the flow path may look like inside an apartment once the apartment door is opened along with the bedroom window. The thermocouple in the kitchen and in the living room were adjacent and likely just outside of the flow path. This indicates the temperatures reported in the kitchen and living room were likely even lower than what was actually encountered in the flow path by firefighters on the suppression crew.

Temperatures in both the kitchen and living room were above 300 °F at the time of entry by the suppression team. Without timely suppression utilizing a flowing hoseline, conditions along the flow path to the fire compartment would continue to deteriorate until water was directed onto the base fuels.

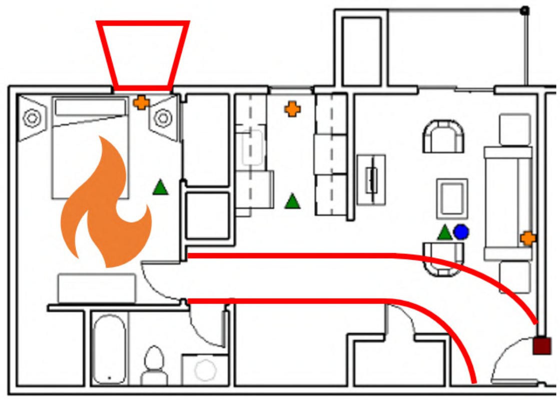
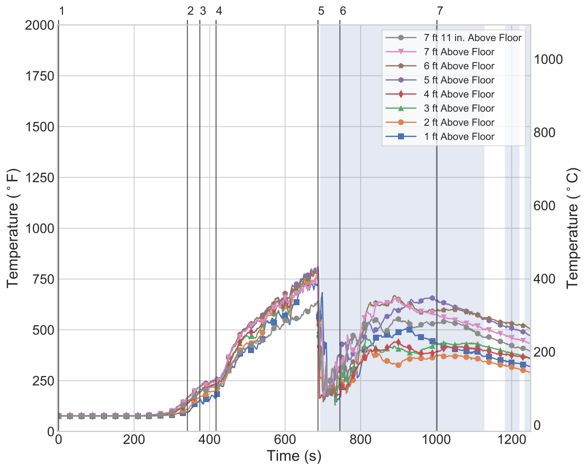


Figure 5.9: Example flow path for a bedroom fire in an apartment with the fire room window and apartment door open.

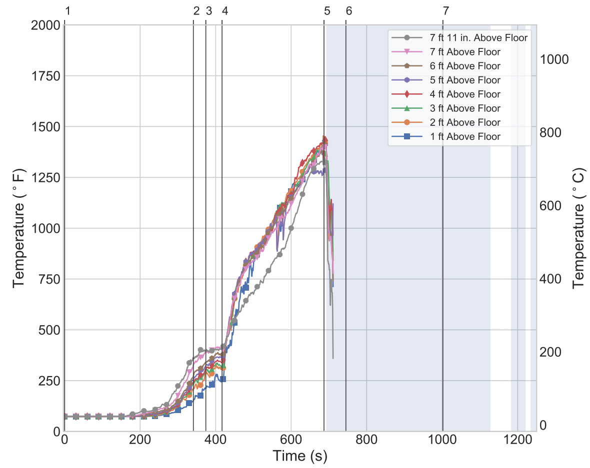
Additionally, Experiment 5 in this series is another example of the need to cool as you advance. The lower-level terrace fire was ignited with the apartment door left open. This allowed the buoyant fire gases to exhaust out of the fire apartment and rise through the stairwell. Once the sliding glass door in Apartment F was opened, the enclosed stairwell became a chimney. The intake was the open sliding glass door in the fire apartment (Apartment J), and the exhaust was the open sliding glass door in Apartment F above (vertical vent). The exterior entry door to the stairwell was located on the first floor, halfway up the chimney. At the time of the first firefighter intervention, temperatures in the stairwell were uniform floor to ceiling on each respective level because the enclosure was serving as an exhaust path only, with no stratification of cooler temperatures lower in the space. See Figure 5.10 for conditions upon opening the exterior breezeway door (the second vertical vent). Thick, dark, and turbulent smoke moving at a high velocity were a tell-tale sign for the need to flow water and cool the space before advancing further into the structure/compartment.

Figure 5.10: Conditions faced by the suppression crew as they opened the exterior breezeway door for entry and suppression in Experiment 5.

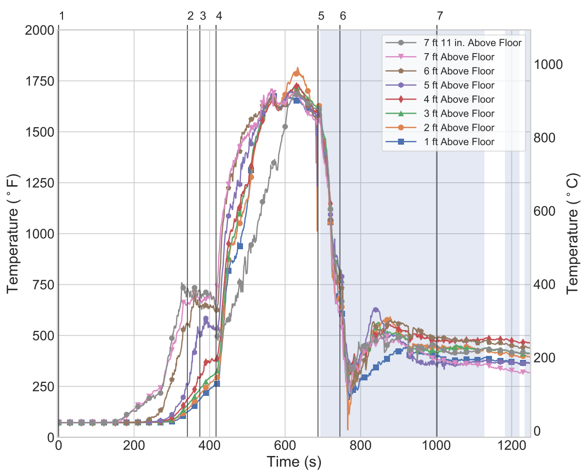
As firefighters opened the exterior entry door, they immediately began to flow water in attempts to cool both gases and surfaces as they advanced. This water application was necessary for them to even occupy the space as they were combating temperatures on the first floor alone of greater than 1250 °F at the time of entry (see Figure 5.11 for temperatures on each level of the stairwell). From the suppression crew's position on the first-floor landing, they were not able to get water into the fire apartment based on the structure configuration and orientation. The suppression crew continued to flow, which allowed them to occupy the space, but it was not until an exterior line applied water from side C onto the burning surfaces that the advance of the interior suppression crew down the stairs and into the fire apartment was possible.



(a) Second-Floor Stairwell



(b) First-Floor Stairwell



(c) Lower-Level Stairwell

	Action/Event	Time (s)
1	Ignition	0
2	Close Apt. H door	341
3	Flashover in living room	374
4	Open Apt. F sliding glass door	417
5	Open exterior door; begin interior suppression	687
6	Begin exterior water application	745
7	End exterior water application	1002

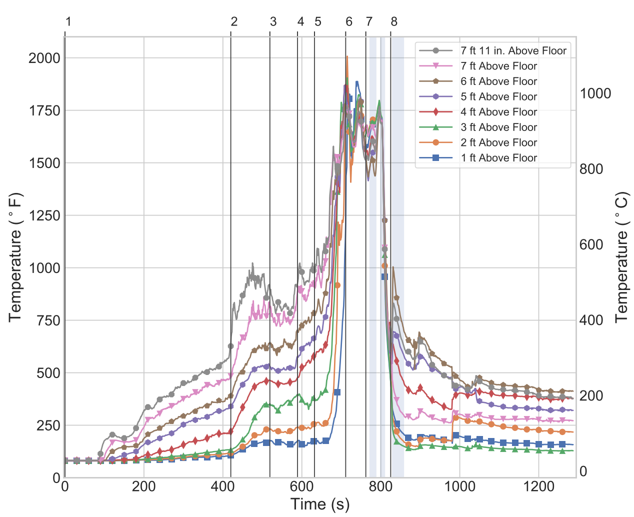
Figure 5.11: Stairwell temperatures for Experiment 5. The first-floor thermocouple was impacted by the hose stream during suppression at around 700 s (11:40), so data thereafter is omitted. Blue shaded regions indicate time and duration of water flow.

5.1.6 Alternative Water Applications to Ensure Sufficient Distribution

Previous research into water application as a part of the fire attack study [5, 7] highlighted the importance of water dispersion within a compartment, particularly alternative means for creating a broken stream improved water mapping within a compartment. A traditional exterior application of water into a fire compartment used a straight stream at a steep angle from a fixed position. This approach maximizes surface/fuel cooling in the compartment and as a result is generally successful at reducing the heat release rate of a fire. However, due to the momentum of the water, the majority of the water is dispersed around the perimeter of the compartment. Depending on the layout of the fuel within the compartment, the lack of water onto the center of the floor of the of the compartment can allow regrowth during the transition time for the crew(s) to move to the interior of the structure to complete suppression. During single-family acquired structure experiments, alternate means of creating a broken stream were incorporated as part of the exterior fire control tactic:

> "It should also be noted that even if the traditional straight stream, steep-angle approach appears to have knocked down the fire, regrowth is an important concern until the nozzle team has made it to the fire compartment from the interior for complete fire extinguishment. To minimize regrowth potential, the lintel hit may be considered as an integral component to exterior water application... [9]."

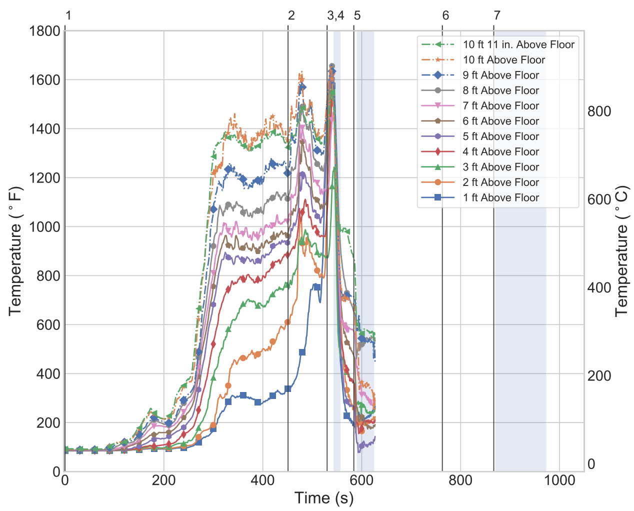
The lintel hit, or breaking up the hose stream on the upper edge of a window frame in way that deflects the water spray into the fire room, was used as part of the exterior fire control tactic in this experimental series. Experiments 3B and 4B utilized the lintel hit after an initial exterior water application with a straight stream pattern. The duration of water application during the lintel hit was at the discretion of the suppression crew (approximately 11 s). From their vantage point, the transition to the interior occurred after all reachable surfaces were sufficiently coated with water. The drop in living room (fire room) temperatures in Experiment 3B, a sign of a reduction in fire heat release rate (see Figure 5.12). show the impact of the tactic. Exterior fire control dropped temperatures from above 1500 °F floor-to-ceiling down to 680 °F 1 in. below the ceiling and 450 °F 1 ft above the floor. Following the transition to the interior, temperatures below 5 ft continued to decrease, while temperatures above 5 ft increased in the 2 s immediately following the crew making entry due to the introduction of air from the stairwell. Living room temperatures at all elevations steadily declined within 4 s of interior water application.



	Action/Event	Time (s)
1	Ignition in kitchen	0
2	Ignition in living room	420
3	Kitchen window failed	522
4	Vent other half of sliding glass door	589
5	Flashover in kitchen	632
6	Flashover in living room	714
7	Begin exterior fire control	768
8	Open apartment door; begin interior suppression	825

Figure 5.12: Living room temperatures for Experiment 3B. Blue shaded regions indicate time and duration of water flow.

Experiment 4B also utilized a lintel hit as part of the exterior fire control tactic. Prior to water application, living room temperatures ranged between 1200 °F and 1650 °F (see Figure 5.13). The first suppression action was sweeping the eave above the living room sliding door for 8 s. The nozzle firefighter then directed the hose stream at the sliding glass door lintel for another 8 s to disperse water in the living room. The exterior water application dropped temperatures throughout the living room and at the time the suppression crew made entry to the fire apartment, temperatures ranged between 800 °F near the ceiling and 200 °F near the floor. In this experiment, temperatures at all elevations continually decreased through the transition.

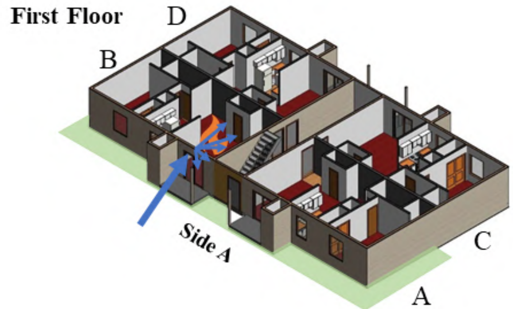


	Action/Event	Time (s)
1	Ignitions in kitchen and living room	0
2	Vent kitchen window	451
3	Flashover in living room	530
4	Exterior fire control	541
5	Open apartment door; begin interior suppression	586
6	Open bedroom window	763
7	Hydraulic ventilation	867

Figure 5.13: Living room temperatures for Experiment 4B. Data after 555 s (9:15) is omitted because the thermocouple signals became irregular due to damage during suppression. Blue shaded regions indicate time and duration of water flow.

Using the lintel to apply a broken hose stream into a fire room utilized here dropped temperatures throughout the fire compartment and reduced the regrowth potential in Experiments 3B and 4B. Figure 5.14 shows the lintel hit employed at the end of exterior fire control in Experiment 3B as well as a depiction of how the stream would break up following impact with the lintel. The lintel improved water dispersion within the living room during exterior fire control and limited the potential for fire regrowth during the crew's transition to the interior.


(a) Lintel Hit from Firefighter Perspective



(b) Depiction of Stream Impact

Figure 5.14: Video still from suppression crew and representative flow impact of the lintel hit employed as part of the exterior fire control in Experiment 3B.

5.1.7 Impact of Isolation

Several prior UL FSRI research studies have shown the positive impact on occupant survivability of a closed door during a residential fire [1, 2, 4, 7, 8]. Results from the fire attack study, which incorporated the use of purpose-built victim packages, led to a tactical consideration pertaining to search operations and closed doors titled *Search Consideration: Closed Doors Significantly Increase Occupant Survivability* that in part states:

> "A victim located in a bedroom during a search with a closed door between them and the fire has a much higher likelihood of survivability than a victim with an open bedroom door [7]."

Depending on the nature of the fire department response, consideration should be given to the potential for isolation of the fire compartment from the rest of the structure until the hoseline is in place and ready to flow. In Experiment 1E, the bedroom (fire room) door closed due to pressure changes in the apartment during fire growth. This isolated the fire compartment from the rest of the apartment and limited further temperature rise and change in gas concentrations throughout the kitchen and living room. Isolation of the fire compartment from the remaining occupied space in the apartment limited the smoke layer descent to approximately 5 ft (see Figure 5.15a). In contrast, Figure 5.15b shows conditions without the fire room isolated from the remainder of the apartment. Both of these images were taken at the time of firefighter entry, which was 265 s post ignition for Experiment 1E and 237 s post ignition for Experiment 1D. The resulting compartment isolation improved the survival chances for potential occupants in the space because there were no measurable changes to gas concentrations (measured at 4 ft) and temperatures at 4 ft remained near 100 °F. A positive impact was produced by limiting further fire growth and limiting the deterioration of conditions in the remainder of the fire apartment.

(a) Experiment 1E Isolated Fire Room (b) Experiment 1D Non-Isolated Fire Room

Figure 5.15: On the left, living room conditions after the fire room was isolated via a closed door in Experiment 1E prior to firefighter entry at 265 s post ignition. On the right, living room conditions without fire room isolation in Experiment 1D prior to firefighter entry at 237 s post ignition.

Additionally, it is important to recognize the importance of closed doors to isolate spaces remote from the fire apartment. Experiment 5 was conducted to examine a lower-level apartment fire with exposures above. The fire was located in Apartment J with exposures on the second-floor in Apartments F and H. From the time of ignition, both doors to Apartments F and H were open, which allowed smoke and fire gases to flow into those apartments. The door to Apartment H was closed 341 s post-ignition, which could simulate an occupant realizing the presence of a fire and isolating themselves, or responding firefighters searching the building and controlling doors as they proceeded. Isolation of the apartment by closing the door prevented temperatures from rising above 100 °F for the duration of the experiment. On the stairwell landing outside of the apartment, temperatures rose above 700 °F prior to the start of suppression. Similarly, in Apartment F, where the door remained open and the living room sliding glass door was opened at 417 s post-ignition, ceiling temperatures exceeded 650 °F.

Figure 5.16 shows the post-fire damage to the second-floor stairwell landing in Experiment 5. The entryway immediately left of the picture led into Apartment F, which had the door open for the duration of the experiment. Further along the left wall, the entryway to Apartment H is visible with minimal damage due to the early isolation of the apartment from the fire below by closing the door.

Figure 5.16: Post fire conditions as seen from the second-floor landing in Experiment 5. Note the extreme damage to the area with a limited view into Apartment H, which was isolated early into the experiment, maintaining survivable space.

Figure 5.17 shows the post-fire condition of the two second-floor exposure apartments, one with the door closed (Apartment H) and one with the door open (Apartment F). Note the condition of the furniture in Apartment F (see Figure 5.17b). The sofa shows signs of pyrolysis, which means the temperatures were sufficient to decompose the polyurethane foam. Although there is noticeable soot coverage throughout the apartment, the lack of flame damage and measured oxygen levels below 5% indicates the gases in the apartment were too fuel-rich to support combustion.

(a) Apartment H (Isolated) Post Fire (b) Apartment F (Non-Isolated) Post Fire

Figure 5.17: Example of post fire damage to the second-floor exposure Apartments H and F from Experiment 5.

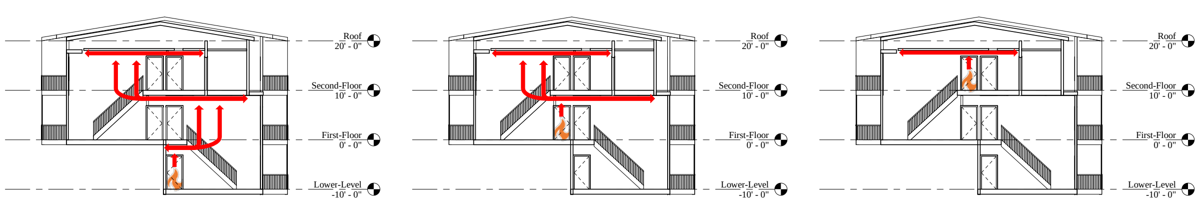
A closed door also limited the transport of high-temperature combustions gases into the adjacent lower-lower apartment, Apartment I. As temperatures in the stairwell on the lower level reached peak values of 1700 °F, the closed door to Apartment I limited peak temperatures to 500 °F at the ceiling while temperatures at 3 ft and below remained below 100 °F for the duration of the experiment. Figure 5.18a shows the damage to the stairwell side of the common wall to Apartment I and Figure 5.18b shows the interior conditions of the apartment at the conclusion of the experiment which highlights the importance of isolation.

(a) View from the Stairwell into Apartment I (b) Living Room and Kitchen of Apartment I

Figure 5.18: Example of post fire damage to the lower-level exposure Apartment I from Experiment 5.

5.2 Protection of the Egress Stairwell

In the multi-family garden-style apartments utilized in these experiments, the predominant egress pathway for an occupant to self-evacuate was through the common enclosed stairwell. The hazard to an occupant is dependent upon their exposure to heat and toxic gases, which is generally higher based on an occupant's proximity to the fire location and elevation within a given space. Buoyancy-driven flow of high-temperature combustion gases can spread the hazard through the egress path, potentially trapping occupants. Figure 5.19 shows an approximation of how the smoke rose throughout the stairwell, ultimately filling from the top down, based on initial fire location. There is no predisposition that a fire is likely to occur on one particular level versus another, so it is important to recognize the stairwell layout and the principle that buoyant gases will fill a space from the top down.



(a) Lower-Level Fire (b) First-Floor Fire (c) Second-Floor Fire

Figure 5.19: Example gas spread in the enclosed stairwell based on initial fire location.

A closed apartment door is an effective barrier between the apartment and the stairwell. Across this experimental series, 11 of the 13 experiments were conducted with the door to the fire apartment closed prior to ignition. In the closed apartment door experiments, the CO concentrations and FEDs measured in the stairwell prior to intervention were negligible (FED < 0.1), while the two open door experiments had elevated FEDs and CO concentrations, as shown in Table 5.4.

Table 5.4: Stairwell Occupant Exposure with Apartment Door Open Prior to Intervention

Exp #	Location	Exterior Door Time [s]	CO at Exterior Door [ppm]	FED at Exterior Door Open
1B	Second Floor	600	20300	30.6
	First Floor	600	4700	1.77
	Lower Level	600	-	0.36
5	Second Floor	687	10100	7.90
	First Floor	687	10100	17.5
	Lower Level	687	3500	3.32

Even for experiments in which there were multiple rooms of fire (Scenarios 3 and 4) and the fires burned for several minutes in a post-flashover state within the apartments, the closed apartment door limited the spread of the toxic gas and thermal hazard to the enclosed stairwell. During Experiments 1B and 5, the two experiments with an open apartment door prior to ignition, there was an exchange of hot gases into the stairwell and cool gases into the fire apartment throughout each experiment. This led to the accumulation of incapacitating FED values in the stairwell. Values ranged from 0.3 to approximately 31 by the time of first firefighter intervention.

The value of isolation of remote apartments can be shown from Experiment 5 through a comparison of temperatures in two second-floor apartments following a lower-level fire with an open apartment door. Both units had open apartment doors prior to ignition. In Apartment H, the apartment door was closed 341 s after ignition, simulating an occupant or searching firefighter isolating the apartment. Peak temperatures below 5 ft remained under 85 °F. In Apartment F, the door remained open and the living room sliding glass door was opened at 417 s after ignition, simulating an occupant moving to their balcony. This action put the apartment in the exhaust portion of the newly established flow path. In this case, 1 ft temperatures peaked at 300 °F and 5 ft temperatures peaked at 590 °F. Based on the Utech thermal class definitions for firefighters in PPE (using only the temperature criteria), Apartment F would remain a routine exposure while Apartment H would range between an ordinary and emergency exposure [33].

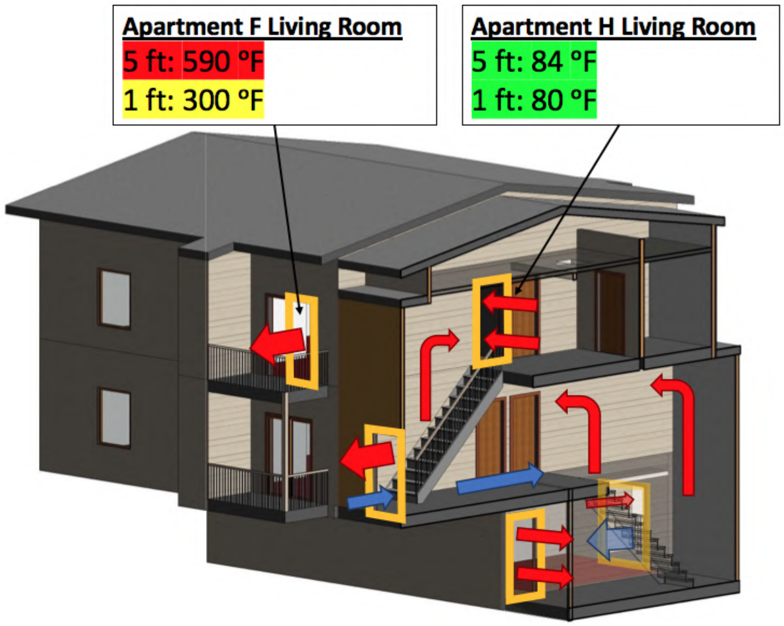


Figure 5.20: Peak temperatures in exposure apartments for Experiment 5. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

In all experiments, the FED at the stairwell measurement locations increased from the time of apartment entry to the end of the experiment. The areas of highest hazard existed on the fire floor and floor above the fire. The second-floor stairwell location generally had the highest measured exposures (FED and FER) from the start of firefighter intervention to the completion of experiments. Additionally, potential occupants located in the stairwell on the fire floor were exposed to the highest temperatures. Occupants located below the fire floor were exposed to the lowest temperatures and toxic gas concentrations. The final toxic FED values (Table 4.4) indicated an increased potential for incapacitation (FED > 0.3) on at least one floor within the stairwell for six of the 11 experiments, indicating the importance of searching exposure spaces on arrival and controlling/closing doors.

Of the five experiments where the FED on all floors stayed below 0.3, the intervention either began with an initial exterior fire control or included tactics employed in parallel. For the two experiments (Experiments 3B and 4B) that included an initial exterior suppression, the initial water flow reduced temperatures and subsequently pressures through gas contraction. As a result, when the suppression crew immediately moved to the interior to complete extinguishment, the temperatures and velocities of the gases that flowed into stairwell were reduced (see Section 4.10). This lessened the hazard for potential occupants in the stairwell.

For the three experiments that leveraged parallel tactics, two used door control (Experiments 1D and 2B) and one used PPA (Experiment 2A), with the goal to minimize the transport of gases into the stairwell concurrent to interior suppression. The door control experiments utilized a firefighter at theapartment door to keep the door closed as far as allowed by the hoseline. By limiting the potential exhaust area into the stairwell, a larger pressure differential between the apartment and stairwell would be needed for gases to flow into the stairwell compared to a fully opened door. As a result, in the two door-control experiments, less combustion products flowed into the stairwell. For the PPA experiment, the suppression crew leveraged the increased pressure developed in the stairwell from the fan flow to minimize the flow of combustion gases into the stairwell. This experiment also utilized a vent ahead of the suppression crew so that pressure in the stairwell would drive flow through the apartment and out of the exhaust vent.

(a) Interior Suppression

(b) Initial Exterior Suppression

(c) Door Control

(d) Positive Pressure Attack

Figure 5.21: Interior conditions following entry to the fire apartment for several different tactical options.

Consideration should be given to employ suppression and ventilation tactics that may lessen the flow of combustion gases into shared common spaces. Previous research has shown that effective exterior water application can improve conditions with a fire compartment [7, 9]. Although not an option for every fire, during these experiments exterior water application was shown to have a positive impact regarding the lessening of the flow of high-temperature combustion gases out of the fire apartment upon entry. This approach should be followed by the suppression crew moving to the interior of the building to complete suppression. While conducting interior suppression operations (resource availability permitting), the suppression crew should consider tactical options such as door control and the use of exterior fans. Similar to any tactical decision, care should be given to assess on-scene variables such as building construction and weather. Finally, consideration should be given to keep isolation in place throughout shared spaces by keeping remote doors closed to limit the spread of combustion gases into exposure units.

Finally, it is important to recall from the definition of FED (see Section 4.1) that the exposure risk does not end with suppression. The FED will continue to rise as long as an occupant is proximal to combustion gases. Therefore, consideration should be given to post-knockdown smoke removal. Prior research in single-family homes [9] showed the importance of post-knockdown horizontal ventilation. In these experiments, hydraulic ventilation (see Section 4.5) and PPV (see Section 4.6) were shown to create unidirectional flows through the fire apartment, subsequently lowering temperatures and removing smoke.

5.3 Timeline of Coordination

Previous research has shown that fires involving typical residential furnishings and ventilation openings will be limited by the amount of oxygen available to support fire growth and are likely to become ventilation-limited [41]. If ventilation was provided to a ventilation-limited fire (i.e., fire self-ventilates through window breakage, a front door is opened for access, or horizontal or vertical ventilation) and suppression was delayed, the ventilation would increase the oxygen available for combustion. When additional oxygen was provided to a ventilation-limited fire, the heat release rate of the fire increased [1, 41]. In the simplest sense, then, minimizing the time between ventilation and suppression limits the amount of oxygen that can react with high-temperature fuel gases before suppression can cool gases and extinguish the fire. On the fireground, this is not always so trivial. An actual incident involves more moving pieces than simply suppression and ventilation (e.g., building geometry, fire location and extension, construction type, existing and potential ventilation/flow paths, access, weather, search, rescue, and available resources), which can impact the timing of these tactics.

As the following sections will detail, consideration should be given to the impact of fire dynamics on the timing of ventilation operations relative to suppression operations. Although many factors can influence the timing of the fire dynamics response to fireground operations (e.g., apartment volume, apartment layout/compartmentalization, fuel load, construction, etc.), it is important to recognize the changes that can occur and the physics that drive the changes.

5.3.1 Uncoordinated Ventilation and Suppression

In this series of experiments several examples provide insight into the effects of uncoordinated ventilation and suppression. Although not a direct example of uncoordinated ventilation, the fire development and smoke movement due to the open door of a lower-level apartment at ignition in Experiment 1B were important to establish the impact of that ventilation were the door to be opened with delayed suppression. The ventilation opening to the common stairwell provided the bedroom fire with more oxygen when compared to the bedroom fire in a lower-level apartment without ventilation (Experiment 1A). The ventilation resulted in higher temperatures at the floor and a longer duration of elevated temperatures in the fire room. The open apartment door allowed an exchange of hot and cool gases between the fire apartment and the common stairwell, resulting in a CO concentration of 2% (20,000 ppm) at 4 ft and 160 °F temperatures throughout the second-floor landing in the stairwell prior to fire department intervention at 600 s post-ignition.

Similarly, Experiment 5 was a lower-level apartment fire with the apartment door open. It differed from Experiment 1B in that the fire started in the living room and the living room sliding glass door was open prior to ignition. Two apartment doors on the second floor were also open. The initial ventilation configuration was sufficient for the living room to flashover. Additionally, the second floor landing had CO concentrations of approximately 0.4% (4000 ppm) and temperatures between 200 °F and 250 °F prior to fire department intervention at 415 s. Until this point, the ventilation in Experiment 5, like Experiment 1B had occurred prior to ignition. That said, the additional ventilation to the lower-level apartment fire resulted in flashover in the fire apartment and more severe exposure conditions in the stairwell.

At 415 s, additional ventilation was provided during Experiment 5 when a second-floor apartment living room sliding glass door was opened. This uncoordinated ventilation caused the flows within the flow path established between the lower-level sliding glass door and second-floor sliding glass door to become unidirectional. Air was entrained through the lower-level living room sliding glass door, which increased the heat release rate and smoke production, and combustion gases were exhausted through the second-floor living room open sliding glass door. In the 270 s (4.5 min) from ventilation to the start of suppression, fire room temperatures increased from 1730 °F to 1980 °F. Second-floor stairwell CO concentrations 4 ft above the floor increased to 1.0% (10,000 ppm), and second-floor stairwell temperatures increased from 250 °F to 800 °F. Conditions elsewhere open to the flow path worsened: Peak lower-level stairwell temperatures increased from 670 °F to 1710 °F, peak first-floor stairwell temperatures increased from 400 °F to 1420 °F, and peak second-floor Apartment F temperatures increased from 200 °F to 680 °F.

Experiment 3B, a first-floor apartment with a kitchen and living room fire, and Experiment 4B, a second-floor apartment with a kitchen and living fire, are two additional examples of uncoordinated ventilation. In both experiments, the living room sliding glass door was open prior to ignition. In Experiment 3B, fire growth led the kitchen window to fail 522 s post-ignition, but the fixed pane of the living room sliding glass door was vented by firefighters 589 s post-ignition. Kitchen temperatures prior to ventilation were stratified between 380 °F and 1690 °F but reached flashover within 43 s of the sliding glass door ventilation. The additional ventilation increased living room temperatures stratified between 630 °F and 1020 °F to flashover in 125 s. In Experiment 4B, kitchen window was vented by firefighters 451 s post-ignition. Within 79 s, the living room transitioned to flashover.

In these experiments, where ventilation-limited fires were provided additional ventilation in the absence of suppression, temperatures increased and the fire apartments transitioned to flashover. Although the time to flashover varied across the experiments based on conditions such as the efficiency of the vent (e.g., door versus window), the location and proximity of the vent relative to fire etc., temperature rises were measured immediately following the additional ventilation. It is important to be deliberate with fireground ventilation, especially as it pertains to the timing of suppression.

5.3.2 Coordinated Ventilation and Suppression

For 11 of the 13 experiments, the experiments were designed to study fire behavior in a singular apartment and the impact of tactics on tenability in the apartment and common stairwell. For all but one of the 11 experiments, the apartment door of the fire apartment door was closed at the time of suppression. From research on the impact of ventilation, "Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction," the tactical consideration *Forcing the front door is ventilation* was developed [1]. Opening the front door (in these experiments, the apartment door), can introduce oxygen to a ventilation-limited fire and result in an increase in heat release rate of the fire. In these experiments, the suppression crew proceeded with a flow-and-move approach as soon as entry was made to the apartment.

In Experiments 1C and 1D, additional ventilation was provided prior to entry to incorporate a tactical consideration from a previous study. A tactical consideration from the fire attack study *Water Flow Can Impact Flow Path* showed that the air entrainment from a manipulated hose stream can be advantageous during interior advancement and suppression [7]. The suppression crew in the fire attack study moved from the exterior entry door toward the already ventilated fire room at the end of a long hallway. The flow-and-move method of hoseline advancement caused all previous bi-directional flows through the exterior entry door to become intake (due to entrainment and flow reversal) as exhaust was re-directed out of the fire room window. This improved conditions throughout the compartment.

The apartments in this study were laid out such that the apartment entry door led into the living room, followed by the kitchen/dining room area, and then the bedroom. A vented bedroom window placed the ventilation openings on opposite ends of the apartment layout, similar to the structure design in the fire attack study. The close timing between ventilation and suppression in Experiments 1C and 1D was designed to take advantage of the previous findings that a controlled and coordinated ventilation opening ahead of the operating hoseline was beneficial. No initial ventilation was provided in either experiment, and ventilation was provided in the fire room approximately 12 s prior to apartment entry and suppression for Experiment 1C, and 9 s prior for Experiment 1D.

Prior to ventilation, only smoke was visible through the bedroom window during both experiments. Ventilation of the bedroom window resulted in an immediate increase in visible burning within the fire room and fire exhausted from the window and continued until the suppression crew got water into the bedroom. In Experiment 1C, fire room temperatures rose immediately following ventilation, increasing between 95 °F and 295 °F within the 12 s prior to interior suppression. In Experiment 1D, growth of a similar magnitude was observed, but temperatures did not begin to increase until roughly 10 s after horizontal ventilation, after the apartment door was opened. Fire room temperatures in Experiment 1D increased between 95 °F and 275 °F. While fireroom temperatures increased following ventilation (more information can be found in Section 4.7), living room ceiling temperatures and 4 ft temperatures remained stable, as shown in Table 5.5.

Table 5.5: Living Room Temperatures in Experiments 1C and 1D

Exp #	Temperature at Window Vent [°F]	Temperature at Door Vent [°F]	Temperature at Suppression [°F]	Temperature after Suppression [°F]
1C	Ceiling: 460 4 ft: 310	Ceiling: 460 4 ft: 310	Ceiling: 430 4 ft: 240	Ceiling: 205 4 ft: 135
1D	Ceiling: 430 4 ft: 270	Ceiling: 430 4 ft: 275	Ceiling: 410 4 ft: 273	Ceiling: 185 4 ft: 115

The CO concentrations measured 4 ft above the floor in the living room continue to increase following the additional ventilation. As the apartment door was opened, a new flow path was created in the fire apartment that allowed combustion gases to flow toward the common stairwell. This flow of gases toward the open door before suppression started (approximately 4 s) led to additional mixing within the space and an increase in gas concentrations. In both experiments, the gas concentrations dropped during suppression. These results following coordinated ventilation show that the temperatures and CO concentrations did not drastically increase after ventilation compared to the uncoordinated cases described in Tactical Consideration 5.3.1, but also do not show drastic improvements.

Table 5.6: Living Room Carbon Monoxide Concentrations in Experiments 1C and 1D

Exp #	CO at Window Vent [% (ppm)]	CO at Door Vent [% (ppm)]	CO at Suppression [% (ppm)]	CO after Suppression [% (ppm)]
1C	0.8 (8000)	1.2 (12,000)	1.4 (14,000)	0.4 (4000)
1D	0.4 (4000)	0.7 (7000)	0.9 (9000)	0.5 (5000)

In Experiments 2A and 2B, the bedroom (fire room) window was open from the time of ignition as part of the initial ventilation configuration. These two experiments represented a self-ventilated fire prior to fire department intervention. Ventilation and suppression were coordinated through the opening of the apartment door once the suppression crew was in place to limit the time of regrowth potential.

As the suppression crew made entry to the breezeway, and then entered the fire apartment, fresh air was entrained by the advancing hoseline and exhausted out of the already vented fire room window. This was indicated by gas velocities at the entry door becoming negative (between -1.0 and -2.0 m/s) during suppression. The initiation of suppression quickly after ventilation allowed the in-flow of fresh air from the common stairwell to aid in decreasing the thermal and toxic exposure within the fire apartment rather than increasing the heat release rate of the fire. Tables 5.7 and

5.8 present living room temperatures and gas concentrations prior to coordinated ventilation and suppression, and temperatures and gas concentrations after suppression. The takeaway is that by establishing a ventilation opening ahead of the hoseline and limiting the time between venting and suppressing the fire, the hazard to interior crews can be limited and victim survivability improved.

Table 5.7: Living Room Temperatures in Experiments 2A and 2B

Exp #	Temperature at Door Vent [°F]	Temperature at Suppression [°F]	Temperature after Suppression [°F]
2A	Ceiling: 590 4 ft: 360	Ceiling: 560 4 ft: 335	Ceiling: 275 4 ft: 210
2B	Ceiling: 525 4 ft: 340	Ceiling: 500 4 ft: 325	Ceiling: 205 4 ft: 115

Table 5.8: Living Room Carbon Monoxide Concentrations in Experiments 2A and 2B

Exp #	CO at Door Vent [% (ppm)]	CO at Suppression [% (ppm)]	CO after Suppression [% (ppm)]
2A	0.9 (9000)	0.9 (9000)	0.7 (7000)
2B	0.6 (6000)	0.6 (6000)	0.1 (1000)

Additional measures such as door control can limit the oxygen available to the fire and also aid in the protection of the egress path. Experiments 1D and 2A both used door control after the suppression crew made entry into the fire apartment. The controlled door limited the effect of the flow path established as the crew made entry to the fire apartment. This limited the gases that flowed through the living room as well as the gases that entered the common stairwell.

PPV was also effective at limiting smoke migration into the common stairwell after opening the apartment door. During Experiment 2B, the fan was put into place 2 s post apartment door ventilation and suppression. The fan flow established unidirectional velocities into the apartment between 0.7 m/s (1.5 mph) and 2.7 m/s (6 mph). This action resulted in the CO concentration on the second-floor stairwell remaining below 0.12%, while in Experiment 2A the CO concentration exceeded 0.12% and took approximately 226 s to decrease below that threshold. Utilizing a fan at the open breezeway door limited the smoke exhaust into the common stairwell during interior operations, which led to a more tenable egress path for potential occupants. Consideration should be given to ensuring suppression is timed closely with, if not before, initiation of the fan operations to ensure the potential hazards from further introduction of oxygen and subsequent fire growth are minimized.

For the bedroom fires, coordinating suppression with apartment door ventilation had a positive affect on fire apartment conditions, even after initially uncoordinated ventilation. The further the distance the fire was from the vent location, the longer it takes for the oxygen to reach the fire. Effectively, the suppression crew had more time to begin suppression. In Experiment 3A, the fire location was moved toward the apartment door (i.e, a living room and kitchen fire). Upon entry to the unit, the suppression crew was met with flames and living room temperatures of approximately 875 °F, as shown in Figure 5.22. Living room ceiling temperatures initially increased from 875 °F to 1025 °F in 2 s, but the coordinated suppression dropped temperatures below pre-open door levels within approximately 6 s, and below 200 °F in 10 s.

Figure 5.22: Conditions in the fire apartment at the time of door open for Experiment 3A.

During Experiment 5, temperatures in the common stairwell were approximately 1420 °F prior to the exterior door opening. The combination of constant water flow and the inflow of fresh air sufficiently lowered temperatures on the first floor, allowing entry into the structure. The hose stream was unable to reach the seat of the living room fire on the floor below, limiting the interior advance of the suppression crew to approximately 10 ft. Coordinated suppression from both the interior and exterior of the structure was necessary for interior advancement to the fire apartment (see Tactical Consideration 5.5). Lower-level stairwell temperatures exceeded 800 °F at the time of exterior suppression, but quickly decreased to approximately 345 °F. This allowed the interior crew to advance to the fire apartment for final suppression.

5.3.3 Coordinated Post-Suppression Ventilation

Although the coordination of ventilation prior to suppression is important for limiting fire growth, the coordination of ventilation post suppression is equally as important for the removal of smoke, enabling a quick return to tenable conditions throughout the structure, and providing better visibility conditions that are better for firefighters conducting interior operations.

The effect of limited (or uncoordinated) ventilation post-suppression is best represented by Experiment 1A, a lower-level bedroom fire in an apartment with no ventilation prior to ignition. Prior to fire department intervention, the fire consumed the oxygen available for combustion in the compartment and effectively self-extinguished. Although gas temperatures in the fire room dropped from a peak near 1600 °F at the ceiling to 200 °F, and pressures returned to ambient levels at the time of entry due to heat loss to the structure, the fire apartment had no ventilation openings beyond natural leakage, so oxygen remained below 15%, and CO was 1% (10,000 ppm) at the time of entry. The apartment door was opened for firefighter ingress into the apartment, which provided ventilation to the apartment. This, however, was inefficient ventilation due to the lack of a fire apartment vent to the exterior and reliance on the natural flow of gases through the stairwell (i.e., high pressure flowing to lower pressure or circulation due to temperature differences). Figure 5.23 shows the flow of gases through the apartment and stairwell following firefighter entry. The reduced buoyancy, lack of pressure difference between the apartment and the exterior, and the long flow path led to a slow exchange of gases. CO concentrations remained elevated above 0.12% (1200 ppm) for approximately 618 s. For a more efficient exchange of gases to the exterior following suppression, consider horizontal ventilation local to the fire compartment.

Figure 5.23: Changes in flow during Experiment 1A following firefighter entry to the apartment. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

Experiments 1D and 2A represent examples of coordinated post-suppression ventilation. Experiment 1D leveraged a combination nozzle with a narrow fog pattern flowing 150 gpm directed out of the fire room within 23 s of suppression to perform hydraulic ventilation. Experiment 2A used a 24 in. gasoline-powered positive pressure ventilator that was positioned 6 ft back from the exterior breezeway door at full-tilt (approximately 20 deg.). The fan was turned on 41 s after the primary suppression actions were complete. CO concentrations prior to fire department intervention were 0.41% (4100 ppm) during Experiment 1D and 0.66% (6600 ppm) during Experiment 2A. Ventilation post-suppression reduced the CO concentration within the fire apartment below 0.12% (1200 ppm) in 147 s in Experiment 1D and 210 s in Experiment 2A. Images of the impact of hydraulic ventilation and PPV can be seen in Figure 5.24. Post-suppression forced-ventilation aided in restoring tenable conditions.

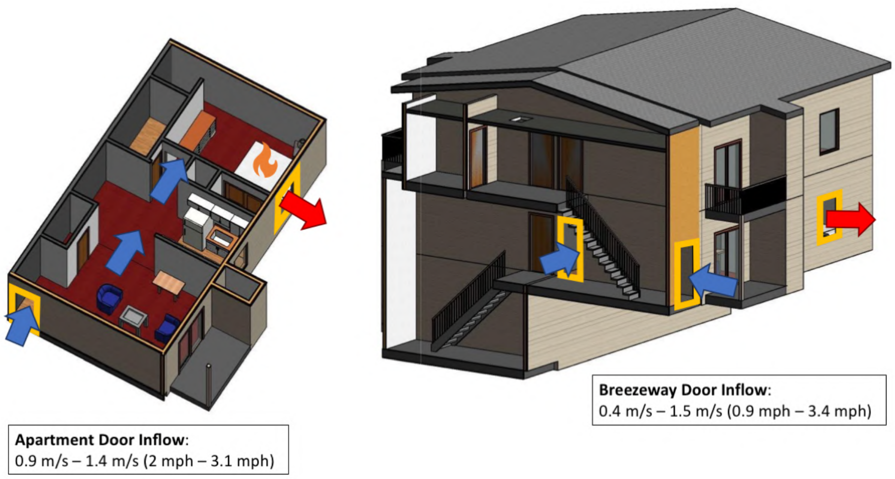
(a) Experiment 1D – Hydraulic Ventilation (b) Experiment 2B - PPV

Figure 5.24: Examples of smoke removal from post-suppression coordinated ventilation.

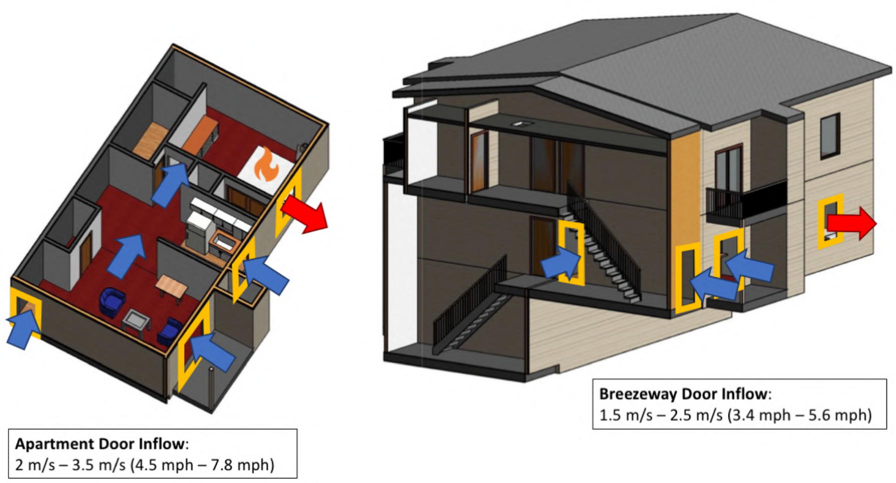
At the start of the forced ventilation tactics in Experiments 1D and 2A, there were two ventilation openings in the fire apartment, the apartment door and the fire room window. Both hydraulic ventilation and PPV created a unidirectional flow through the open stairwell door and fire apartment, but did so in different manners.

Hydraulic ventilation uses the flow of water from the hose stream to entrain air. As the air moves, an area of low pressure is created, which drives flow from surrounding gases that are a higher pressure in the direction of the water flow. Essentially, hydraulic ventilation can be thought of as a pull source or negative pressure ventilation. This is visualized in Figure 5.25a.

With the singular intake (the open apartment door), hydraulic ventilation generated between 2.0 m/s (4.5 mph) to 3.0 m/s (6.7 mph) of flow into the apartment from the stairwell. After additional ventilation occurred in the fire apartment (see Figure 5.25b), intake velocities dropped to 1.0 m/s (2.2 mph) to 2.0 m/s (4.5 mph). The decreased flow through the apartment door indicated the makeup air for hydraulic ventilation was now also being entrained through the open living room sliding glass door and kitchen window. The reduced flow through the common stairwell decreased smoke removal from the stairwell. The increased flow through the living room and kitchen increased the potential for smoke removal of the fire apartment.



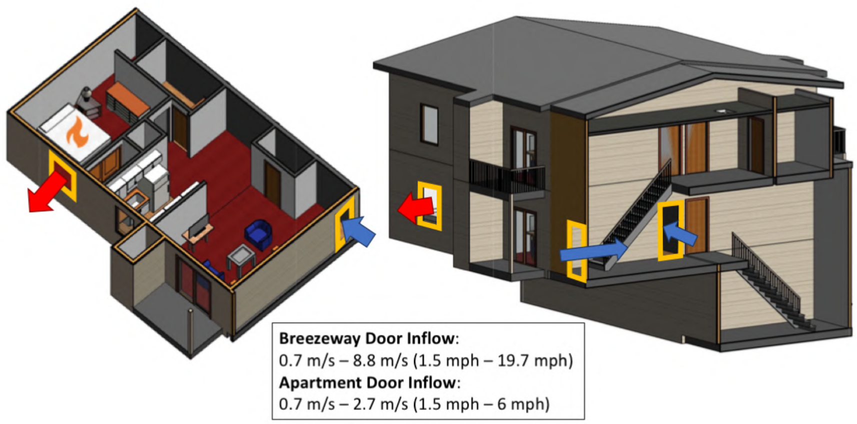
(a) After the Start of Hydraulic Ventilation



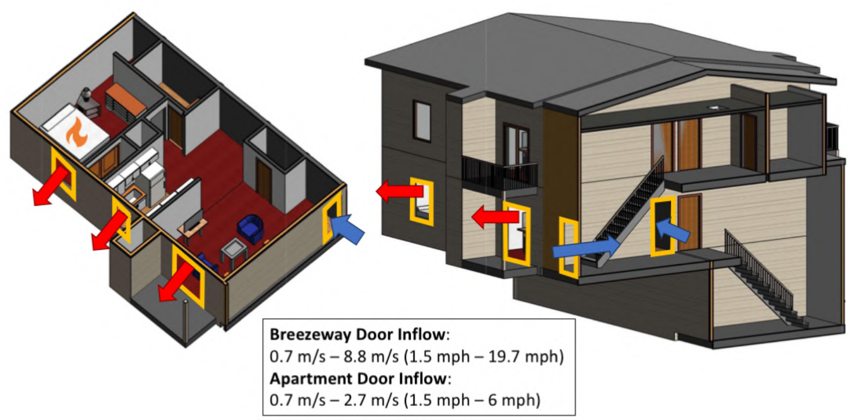
(b) After Ventilating the Kitchen and Living Room

Figure 5.25: Changes in flow during Experiment 1D following hydraulic ventilation and additional horizontal ventilation. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

PPV uses the airflow generated by a fan to create an area of higher pressure, with the idea that the fan is appropriately sized to generate more pressure than the fire. PPV can be thought of as a push source. In Experiment 2A, the PPV fan was set up to push ambient air through the open vents in the fire apartment (see Figure 5.26a). The flow entered the apartment and initially exhausted through the open bedroom window. This was similar to the hydraulic ventilation case. Apartment door velocities ranged between 1.0 m/s (2.2 mph) and 3.0 m/s (6.7 mph) into the apartment. When the additional vents were created (by opening the living room sliding glass door and kitchen window), the apartment door velocities remained nominally unaffected. The difference with hydraulic ventilation was that the additional vents acted as additional exhausts instead of additional intakes (see Figure 5.26b).



(a) After Starting PPV



(b) After Ventilating the Kitchen and Living Room

Figure 5.26: Changes in flow during Experiment 2A following PPV and additional horizontal ventilation. Red arrows indicate the flow of combustion products, blue arrows indicate the flow of fresh air, and the size of the arrows indicate the relative magnitude of the flow. Yellow boxes indicate ventilation openings.

Post-suppression ventilation should be strategically employed to facilitate tenable conditions in common areas as well as the fire apartment. Consideration should be given to focusing on the area of highest immediate hazard based on occupant status and select the tactic that best accomplishes the desired flows. If the egress path is of most concern, additional ventilation in the fire apartment could be held until later in the timeline to facilitate quicker smoke removal in the stairwell. If the stairwell is open to the exterior or not of present concern, additional ventilation openings in the fire apartment will facilitate smoke removal in those locations the quickest.

These experiments in multi-family dwellings confirmed previous research indicating that ventilation should be closely timed and coordinated with suppression actions. Ventilation pre-suppression should be limited, potentially to the fire compartment only, and closely timed with the beginning of suppression. Ventilation post-suppression should be focused on the areas of greatest hazard. Once the fire is knocked down, ventilation of all affected areas may be required to completely clear the structure. Consider the combination of ventilation methods or utilizing doors to change ventilation configurations to accomplish the intent based on the method being deployed. Finally, conditions should be continuously monitored post-suppression to ensure the increased ventilation does not lead to re-growth.

5.4 Size-Up and Construction Considerations of Multi-Family Dwellings

Previous research [8, 9] and LODD/LODI incidents [11, 42–44] have emphasized the importance of a thorough size-up in ensuring firefighter safety and achieving operational goals, including life safety, incident stabilization, and property conservation. Although the specific size-up considerations for a particular incident can include any number of factors, such as staffing, response models, and local policies and procedures, all size-ups of garden-style apartment buildings should include factors such as the type of building construction, changes in grade, and fire conditions found upon arrival.

The fire conditions encountered upon arrival can suggest the point in fire growth the fire has reached. Fires with nothing evident or light smoke showing could indicate a fire that is under-ventilated, as was the case in the Scenario 1 experiments. Fire room temperatures in these experiments peaked between approximately 175 s and 225 s after ignition, shortly before the time of fire department intervention. Following this peak, temperatures started to decrease, indicating they were entering a state of ventilation-limited decay.

Experiments 1C and 1D provided an example of the importance of discipline with regards to ventilation tactics on ventilation-limited fires. Although the smoke conditions at the time of intervention were relatively minor, as shown in Figure 5.27, horizontal ventilation resulted in an increase in visible flaming and fire room temperatures. Note that because ventilation was closely timed with suppression, temperatures in areas of the fire apartment remote from the fire room did not increase. Thus, for scenarios with no smoke or limited smoke showing, ventilation tactics should be undertaken judiciously and be closely timed with suppression, with careful consideration given to the creation of ventilation openings to the exterior of the apartment or the common stairwell.

(a) Experiment 1C (b) Experiment 1D

Figure 5.27: Exterior conditions (smoke showing with no exterior openings) immediately prior to fire department intervention in Experiments 1C and 1D.

Fire showing to the exterior of the structure upon arrival, as was the case in Scenarios 2–4, can similarly indicate a ventilation-limited fire, and ventilation tactics should also be closely timed with suppression. Depending on the construction type, fire venting from the structure can additionally pose the hazard of exterior fire spread. Garden-style apartments are typically classified as either Type III or Type V construction, and can either have combustible or non-combustible siding. For structures with combustible exterior siding, fire venting from windows or other exterior openings has the potential to cause exterior fire spread, as was observed in Experiments 3A and 3B, as shown in Figures 5.28a and 5.28c. Although the extent of exterior fire conditions at the time of intervention in these experiments might suggest a well-advanced fire requiring a high flow rate, the exterior fire in both experiments was controlled with less than 100 gallons from a 1.75 in. handline flowing 160 gpm. Because exterior fire spread might lead to extension into attic spaces or adjacent units, potentially escalating the incident, suppression crew(s) should consider addressing exterior fire spread prior to conducting operations interior to the fire apartment. In addition to limiting exterior fire spread, exterior fire control may help first-arriving crews better understand conditions; namely, whether the fire was solely exterior, or whether it had extended into exposure apartments within the building. Note that even if the exterior cladding of the structure is non-combustible, balconies or other fixtures may still be constructed using combustible materials, and could be targets for exterior fire spread.

(a) Experiment 3A, Pre-Exterior Suppression

(b) Experiment 3A, Post-Exterior Suppression

(c) Experiment 3B, Pre-Exterior Suppression

(d) Experiment 3B, Post-Exterior Suppression

Figure 5.28: Fire conditions on exterior of structure immediately before and immediately after exterior fire control in Experiments 3A and 3B. The exterior suppression action utilized approximately 94 gal and 25 gal in Experiments 3A and 3B, respectively.

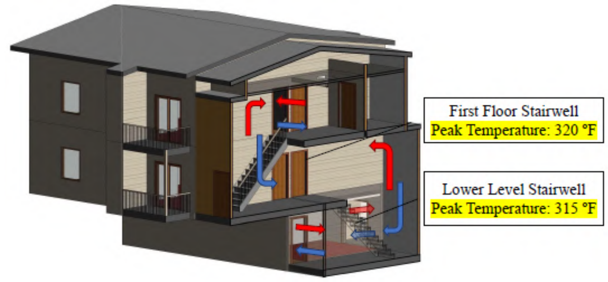
In addition to considering the smoke and fire conditions evident from the exterior of the building, firefighters should also consider the conditions in the common stairwell upon arrival. In particular, first-arriving companies should assess whether the door between the fire apartment and the common stairwell has been compromised. The experiments in Scenarios 1—4 demonstrated that even with post-flashover conditions within the fire unit, the apartment door remained an effective barrier for products of combustion, with minimal exposures within the stairwell prior to the door being opened. If first-arriving units determine the stairwell remains isolated, they may want to consider an alternate means of access to the fire apartment, such as the living room sliding glass door for first-floor or lower-level apartments. Maintaining the isolation of the common stairwell during fire suppression reduces the amount of smoke that can be exhausted into the common stairwell, preserving its use as a means of egress.

If it is not practical to maintain isolation of the common stairwell, or if that isolation has already been compromised, firefighters might consider means of mitigating or reducing the exposure to the common stairwell during suppression operations. Experiments 1D, 2A, and 2B demonstrated that actions such as door control, PPV, and PPA reduced the volume of products of combustion that could be exhausted into the common stairwell compared to when these actions were not taken (i.e., Experiments 1A, 1C, 3A, 3B, 4A, 4B). If the conditions in the common stairwell dictate that it is not a viable means of egress, firefighters should consider alternative means of egress for occupants potentially trapped in apartments, such as ground ladders. The utilization of other interior apartment doors to isolate the potential occupants and sheltering in place are other options.

The location of the fire apartment within the building, and whether it is on a floor below-, at- or above-grade, is another important size-up consideration for firefighters, because top-floor fires will have different considerations than below-grade fires, and vice versa. If the fire apartment is a top-floor unit, there is an increased likelihood of ceiling failure, which can accelerate extension into the attic space. This was the case in Experiment 4A, where ceiling failure in the kitchen enabled extension into the attic. This might be of particular concern in garden-style apartment buildings with interconnected attic spaces without fire stops, where an uncontrolled attic fire could escalate the incident. If first-arriving units determine the fire is in a top-floor apartment, checking for extension would be a high priority.

Previous research has documented the hazards associated with below-grade fires in residential homes [8, 45]. In particular, below-grade fires can place firefighters in the exhaust portion of the flow path, exposing them to elevated temperatures and heat fluxes, which is why firefighters should consider fighting below-grade fires on their own level whenever possible. The results of Experiments 1A, 1B, and 5 showed that similar hazards can exist for below-grade units in garden-style apartments. The magnitude of thermal conditions depended on the flow paths within the structure, and specifically the location of inlets and exhaust points. In Experiment 1A, the temperatures prior to intervention were negligible due to the closed apartment door, which isolated the stairwell and reduced the amount of oxygen available to the fire. In Experiment 1B, there were no exterior ventilation openings prior to the opening of the breezeway door, meaning the only oxygen available for fire growth was in the apartment of origin. The exterior breezeway door was opened after temperatures in the fire room had started to decrease, indicating the fire was decaying due to a lack of oxygen. After being opened, it acted as both an inlet and an outlet, as shown in Figure 5.29a. The inefficient flow path, coupled with the already decreasing temperatures, resulted in peak temperatures at firefighter crawling height (3 ft) of 176 °F and 150 °F at the first floor and lower level measurement locations, respectively. These temperatures were consistent with ordinary and routine operating conditions, respectively.

(a) Experiment 1B



(b) Experiment 5

Figure 5.29: Peak 3 ft temperatures in first floor and lower level of common stairwell for Experiments 1B at exterior door open, and Experiment 5 prior to any ventilation.

The initial ventilation configuration in Experiment 5 was comparable to Experiment 1B, but the living room fire had a source of ventilation through half of the living room sliding glass door (Figure 5.29b). In this configuration, the sliding glass door acted as both inlet and exhaust for the living room fire, while the common stairwell simultaneously filled with products of combustion. Because the living room fire had a constant source of air, it did not enter a state of ventilation-limited decay and transitioned through flashover. As a result, peak temperatures prior to any additional ventilation at 3 ft in the stairwell were higher than in Experiment 1B at 320 °F and 315 °F at the first-floor and lower-level measurement locations, respectively. Both of these temperatures were consistent with ordinary operating conditions. The higher temperatures reflected the larger fire sustained due to the exterior ventilation, but the lack of a separate exhaust from the stairwell kept temperatures within ordinary operating conditions.

Once the Apartment F sliding glass door was opened in Experiment 5, an efficient flow path was created, with an inlet at the Apartment J sliding glass door and an unidirectional exhaust through the Apartment F sliding glass door. This resulted in an immediate increase in stairwell temperatures, with the 3 ft temperature increasing in 45 s from 320 °F to 700 °F at the first floor and 315 °F to 915 °F in the lower level. These stairwell temperatures continued to increase until the exterior breezeway door was opened, at which point the stairwell temperatures were consistent with emergency operating conditions, as shown in Figure 5.30. As the suppression team began to flow-and-move toward the fire room, they were exposed to the severe temperature in the exhaust portion of the flow path. Although flow-and-move suppression decreased temperatures at 3 ft in the lower level, they remained in the emergency operating range, and fire apartment temperatures were unaffected. Once exterior suppression was initiated, temperatures in the stairwell and in the fire apartment immediately dropped.

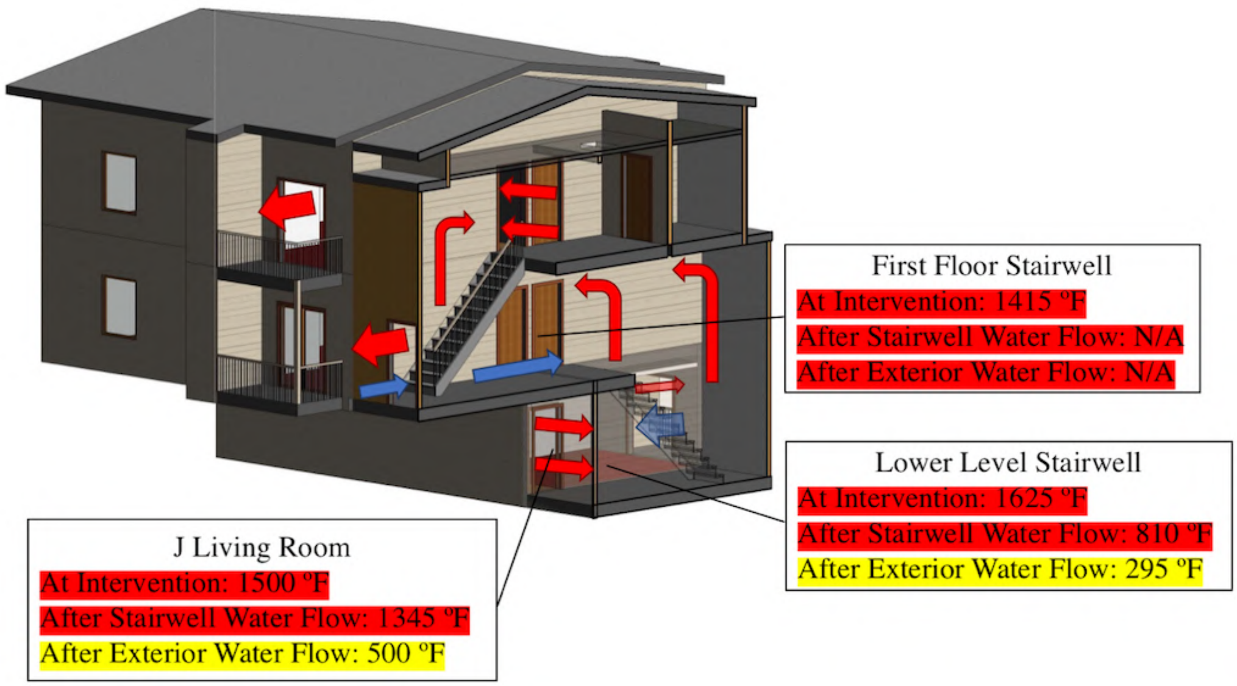


Figure 5.30: Peak 3 ft temperatures in the lower level and first floor of stairwell and fire apartment (Apartment J) for Experiment 5 at intervention, first interior water flow, and first exterior water flow.

The exterior suppression action in Experiment 5 demonstrates the effectiveness of fighting a below-grade fire on its own level rather than making an approach through the exhaust portion of the flow path (see bottom rows in Figure 5.30). Because garden-style apartments can be part of a multi-building group, it may not always be practical for firefighters to achieve a complete 360-degree size-up or to redeploy their hoseline to the opposite side of the building. For this reason, if the reported apartment is a lower-level apartment, or first-arriving units suspect the fire apartment is a below-grade unit, they should consider a line of approach that would allow them to position their apparatus in a way to fight the fire on its own level. Similarly, firefighters should consider coordinating with later-arriving units to achieve a complete 360-degree size-up.

The difference in thermal conditions between Experiments 1A, 1B, and 5 illustrate the variety of possible scenarios for the same fire location, with the differences largely being due to different inlet and exhaust locations. Thus, it is essential that as part of their size-up, firefighters consider the flow paths present within the building and how those flow paths might change and potentially affect thermal conditions in the areas where firefighters are operating or occupants egressing.

5.5 Simultaneous Hose Streams Can Improve Suppression Operations

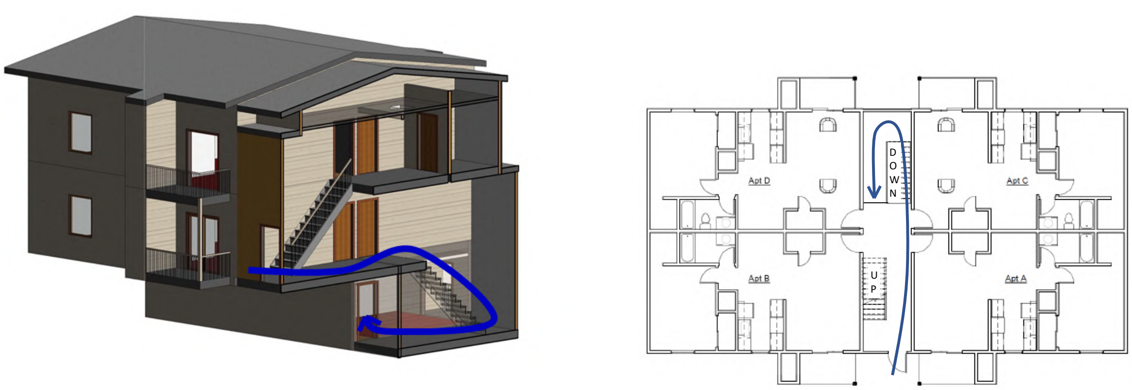
The coordination of suppression with ventilation is critically important for limiting fire growth, reducing the thermal hazard, and improving victim survivability in a structure fire as discussed throughout this study and the research into single family homes and strip mall occupancies [9,46]. Additionally, there can be multiple ventilation or suppression tactics that require coordination with one another to achieve a certain strategy. On any given fire, this can include interior suppression, exterior fire control, or both. Experiment 5 required the use of two hoselines, employing both interior suppression and exterior fire control simultaneously to extinguish the fire in a lower-level apartment.

The fire in Experiment 5 was ignited in a lower-level apartment in the living room. The living room sliding glass door and apartment door leading to the enclosed stairwell were left open from ignition. Two second-floor apartment doors to the enclosed stairwell were left open to examine exposure hazards above the fire. The ventilation openings in the fire apartment allowed for an exchange of fresh air and hot, buoyant fire gases to both the exterior of the structure as well as to the enclosed stairwell. The living room fire transitioned through flashover approximately 374 s post ignition (prior to firefighter intervention) due to a sufficient supply of oxygen that supported continued fire growth in the apartment. The hot, buoyant fire gases that exhausted from the apartment rose through the enclosed stairwell and into the exposure apartments above. The door to Apartment H was closed early into the experiment, which isolated it from the fire below. The door to Apartment F was left open, and shortly thereafter (417 s post ignition), the sliding glass door in Apartment F was opened. This uncoordinated ventilation of the sliding glass door on the second-floor was, in essence, a vertical vent. The vertical ventilation opening in Apartment F increased the flow of fire gas flow into the stairwell, effectively creating a chimney. Fresh air was entrained through the lower-level sliding glass door in the fire apartment and smoke and fire gases were exhausted through the apartment door, stairwell, and out of the second-floor sliding glass door in Apartment F.

Interior suppression was the first tactic employed during this experiment due to the changes in elevation from side A to side C of the structure as seen in Figure 5.31. Firefighters arriving to a similar structure would likely choose the side A entry door for ingress because access to side C was limited and difficult to navigate due to the terrain. The elevation change from the front to the rear was approximately 20 ft, leaving the balcony to the lower-level fire apartment at least 10 ft above the ground. Just prior to opening the exterior door to the stairwell to begin interior suppression, the fire apartment was post-flashover with temperatures floor to ceiling above 1500 °F. Temperatures throughout the building continued to steadily increase.

Figure 5.31: Rear elevation of the fire building for Experiment 5, pictured shortly after ignition.

Knowing that the point of entry to the interior was directly into the exhaust portion of the flow path and one level above the fire, firefighters opened the exterior door to the enclosed stairwell and began flowing water immediately. Suppression was conducted from just inside the threshold of the doorway. The crew worked to coat and cool as many surfaces in the stairwell as possible with water before advancing further. The path of advancement to the fire apartment was a forward push across the first-floor landing, down the staircase to the lower-level, a 180-degree turn back toward side A, a forward push, and final 90-degree turn into the apartment. See Figure 5.32 for the depiction of the required path of advancement for the interior suppression crew.



(a) Isometric View of Path of Travel

(b) Plan View of Path of Travel

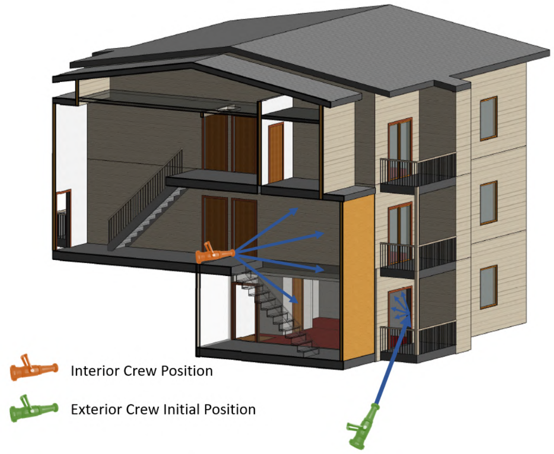
Figure 5.32: Path of advancement for the interior suppression crew during Experiment 5.

The initial water flow from the interior suppression efforts only provided localized cooling for the crew in the stairwell. The localized cooling resulted in a temperature decrease from approximately 1450 °F to 950 °F on the first floor. At this point, the instrumentation on the first floor was hit with the hoseline, compromising the data from this point forward. As lower-level stairwell temperatures decreased from 1620 °F to 820 °F from interior suppression, second-floor stairwell temperatures also decreased from 700 °F to 250 °F. However, due to the change in fire gas flow and the additional vertical ventilation opening via the open front door to the stairwell, the fire apartment temperatures increased further from approximately 1560 °F to 1720 °F as additional air was entrained through the open sliding glass door in the fire apartment.

It should be noted that a hose stream is a line-of-sight tool. With the interior suppression crew positioned on the first-floor landing, they were able to coat the surfaces in the stairwell on all three levels but were not able to get water onto the burning surfaces in the fire apartment nor the burning stairwell linings adjacent to the apartment door. Hot, buoyant fire gases continued to exhaust out of the fire apartment and into the enclosed stairwell despite the continued suppression efforts by the interior crew. The interior suppression crew was able to flow-and-move to the rear of the first-floor landing before calling for exterior fire control from the rear. At this point, the interior crew was unable to descend the staircase to the lower level through the exhausting fire gases and maintained continuous water flow for localized cooling to remain in their position at the top of the staircase to the lower level.

Exterior fire control commenced from side C through the living room sliding glass door to the fire apartment at 745 s (see Figure 5.33a), which shows the initial angle of approach for the flowing hoseline from side C to get water into the fire apartment. Figure 5.33b shows the two suppression crew locations during the simultaneous application of water from both the interior and exterior. Hose steam movement was limited as to not occlude the ventilation opening. Additionally, note the limited amount of fire gases being exhausted from the sliding glass door of the fire apartment as it was serving as primarily an intake with the exhaust flowing through the open apartment door and vertically through the enclosed stairwell. Even despite the angled approach, the exterior fire control was so effective in wetting the base fuels that it nearly extinguished the living room fire during the first application of water from the rear. The hoseline was then repositioned for a more direct application into the fire apartment during a second application of water (see Figure 5.34). Temperatures in the fire apartment decreased from approximately 1710 °F to 115 °F during exterior suppression. Temperatures throughout the exhaust portion of the flow path decreased as well from the lower level to the second-floor and into Apartment F. Temperatures on the lower level in the stairwell decreased immediately from 780 °F to 345 °F during exterior suppression.

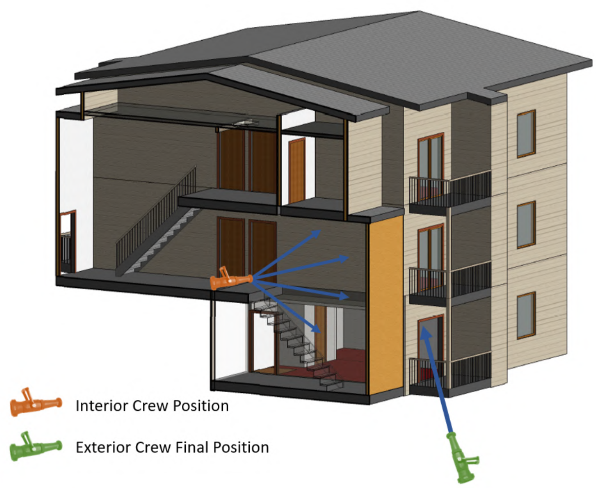
(a) Side C View of Exterior Crew Initial Position



(b) Crew Locations During Initial Applications

Figure 5.33: Suppression crew at the start of exterior fire control on side C of the fire building in Experiment 5, and isometric representation of interior and exterior crew positions during initial simultaneous water applications.

(a) Side C View of Exterior Crew Final Position



(b) Crew Locations During Final Applications

Figure 5.34: Suppression crew after repositioning for exterior fire control on side C of the fire building in Experiment 5 and isometric representation of interior and exterior crew positions during the final simultaneous water applications.

Exterior suppression knocked the fire in the apartment of origin and limited the flow of hot gases into the common stairwell, which allowed the interior suppression crew to continue their advance to the lower level and enter the fire apartment for final suppression. Despite the exterior hoseline being directed into the fire apartment while the interior crew (located in the exhaust portion of the flow path) simultaneously flowed water down the stairs, no negative effects were seen in the stairwell as both methods of suppression worked together to achieve successful knock down.

6 Future Research

The 13 experiments conducted in a multi-family dwelling for this study, built upon prior experiments conducted across numerous studies in single-family structures (both purpose built and acquired) [1–9]. This research explored how coordinated suppression and ventilation affect fire dynamics and exposures to occupants and fire service personnel in the apartment of origin, common stairwell, and exposure apartments.

The three-story, garden-style apartment buildings with combustible balconies and enclosed common stairwells used in these experiments represent just one structure type within the broader category of multi-family dwellings. Multi-family dwellings are generally defined as separate residences of two or more families; however, there is little in the definition that further clarifies the type of structure in which these residences occupy. For example, a single family dwelling could be subdivided to house several families in smaller apartment-style layouts. Additionally, a mid-rise apartment building would fall under the classification of a multi-family dwelling as would a high-rise apartment building, depending on the jurisdiction. Research is needed to continue to address the impact of suppression and ventilation tactics across the range of multi-family structures, specifically related to how the differences in structure type, layout, and construction can impact potentially trapped occupants and firefighters.

Future research needs include experiments in apartments with larger sizes and different configurations. These experiments were conducted in 800 sq ft one-bedroom apartments with an arrangement such that the apartment door and bedroom door were aligned. Changes in volume and layout of the apartments could impact the time to ventilation-limited conditions, the responses to changes in ventilation, and the efficacy of different suppression tactics. Further, in conjunction with the project technical panel, best practices of suppression and ventilation from prior single-family residential research were chosen to be implemented in these multi-family experiments. They were chosen to determine the applicability of residential tactics on different structure types. Research is needed to assess additional tactics in the multi-family environment including the type of suppression method, handline size/flow rate/pressure, ventilation type (e.g., horizontal and vertical), alternate tools for creating isolation, alternate means of preserving the egress path (i.e., vertical ventilation) and the timing typically associated with these tactics.

7 Summary

This study built upon previous residential fireground research by examining the coordination of ventilation and suppression tactics in acquired three-story multi-family dwellings. Experiments were conducted in four separate garden-style buildings. Each building had two lower-level units, four first-floor units, and four second-floor units. Each apartment was approximately 800 sq ft with a single bedroom. The apartments were all connected through a central, common enclosed stairwell.

Bedroom, kitchen, and living room fires were studied on all levels of the structure with four experiments conducted in lower-level apartments, seven conducted in first-floor apartments, and two conducted in second-floor apartments. Firefighter intervention included both exterior fire control and interior suppression with ventilation tactics that included horizontal ventilation, PPV, PPA, hydraulic ventilation, and door control. Fire sizes varied depending on the amount of ventilation provided prior to ignition as well as additional ventilation provided prior to suppression. The main control variables included the location of initial water application, the ventilation method, and the timing of ventilation relative to water application.

Similarity between the apartment configurations and building layouts led to several consistencies regarding fire dynamics and smoke movement:

- Similar to previous experiments in acquired single-family structures, there was no meaningful increase in temperature outside of fire rooms when ventilation tactics were executed in close coordination with (shortly after or shortly before) the onset of suppression.
- For experiments where ventilation occurred with delayed suppression, temperature exposures increased throughout the fire apartment, and in experiments where the apartment door was left open, temperatures and carbon monoxide exposures increased throughout the common stairwell.
- Suppression actions, whether interior or exterior, resulted in a decrease in temperatures and gas concentrations at locations where occupants may potentially be located. Initial exterior actions were shown to lower the potential hazard for firefighter entry to the fire apartment and potential exposures in the enclosed stairwell.
- Opening the apartment door to gain access should be thought of as ventilation; both in terms of its potential to cause fire growth and its potential for smoke movement into the stairwell which could limit the egress for potential occupants in exposure units.
- Ventilation tactics such as door control, positive pressure, and hydraulic that were used both simultaneous with and sequentially post-suppression were shown to limit gas flows into the stairwell.

- After suppression, forced ventilation operations (e.g., PPV or hydraulic ventilation) were effective at drawing air through the fire apartment which further lowered temperatures and increased the rate of gas concentration improvement.

These trends were able to support several of the tactical considerations from previous studies in both purpose-built structures in the laboratory as well as acquired single-family homes. While garden style, multi-family dwellings provide a unique set of exposure challenges, the fire dynamics and resulting impact from suppression and ventilation tactics closely resemble those of the residential fire environment seen in single-family dwellings. It should be noted that the type and coordination of both suppression and ventilation tactics is going to be dictated by the findings during a given emergency incident as well as parameters set forth by a department's response model (staffing and resources).

References

[1] S. Kerber. Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction. Underwriters Laboratories, Northbrook, Illinois, December 2010.

[2] S. Kerber. Study of the Effectiveness of Fire Service Vertical Ventilation and Suppression Tactics in Single Family Homes. UL Firefighter Safety Research Institute, Northbrook, Illinois, June 2013.

[3] S. Kerber and R. Zevotek. Study of Residential Attic Fire Mitigation Tactics and Exterior Fire Spread Hazards on Fire Fighter Safety. UL Firefighter Safety Research Institute, Columbia, Maryland, November 2014.

[4] R. Zevotek and S. Kerber. Study of the Effectiveness of Fire Service Positive Pressure Ventilation During Fire Attack in Single Family Homes Incorporating Modern Construction Practices. UL Firefighter Safety Research Institute, Columbia, MD, May 2016.

[5] C. Weinschenk, K. Stakes, and R. Zevotek. Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Water Mapping. UL Firefighter Safety Research Institute, Columbia, Maryland, December 2017.

[6] C. Weinschenk, K. Stakes, and R. Zevotek. Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Air Entrainment. UL Firefighter Safety Research Institute, Columbia, Maryland, December 2017.

[7] R. Zevotek, K. Stakes, and J. Willi. Impact of Fire Attack Utilizing Interior and Exterior Streams on Firefighter Safety and Occupant Survival: Full-Scale Experiments. UL Firefighter Safety Research Institute, Columbia, Maryland, January 2018.

[8] D. Madrzykowski and C. Weinschenk. Understanding and Fighting Basement Fires. UL Firefighter Safety Research Institute, Columbia, Maryland, March 2018.

[9] J. Regan, J. Bryant, and C. Weinschenk. Analysis of the Coordination of Suppression and Ventilation in Single-Family Homes. UL Firefighter Safety Research Institute, Columbia, Maryland, March 2020.

[10] M. McFall, K. Cortex, and N. Romano. Career Fire Fighter Dies After Becoming Trapped by Fire in Apartment Building - New Jersey. NIOSH F2001-18, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2002.

[11] J. Tarley, S. Miles, M. Loflin, and T. Merinar. Volunteer Fire Fighter Caught in a Rapid Fire Event During Unprotected Search, Dies After Facepiece Lens Melts – Maryland. NIOSH F2011-02, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2012.

[12] M.E. Bowyer, S.C. Wertman, and M. Loflin. Career Captain Sustains Injuries at a 2-1/2 Story Apartment Fire then Dies at Hospital – Illinois. NIOSH F2012-28, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2013.

[13] M. Bowyer, M. Loflin, and S. Wertman. Two Career Fire Fighters Die in a Rapid Fire Progression While Searching for Tenants – Ohio. NIOSH F2014-02, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2015.

[14] M. Loflin, M. Bowyer, S.T. Miles, and S. Wertman. Lieutenant and Fire Fighter Die and 13 Fire Fighters are injured in a Wind-driven Fire in a Brownstone – Massachusetts. NIOSH F2014-09, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2016.

[15] M. Bowyer, S. Miles, and M. Loflin. Career Fire Fighter Dies From an Out-of-air Emergency in an Apartment Building Fire – Connecticut. NIOSH F2014-19, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2017.

[16] D. DeStafano. Garden Apartment Fires: No Walk in the Park. *Fire Engineering*, December 2015.

[17] M. Ciampo. Grab the Dresser. *Fire Engineering*, 163(10), October 2010.

[18] C. Bailey. How to Approach Garden Apartment Fires. *FireRescue1*, September 2007.

[19] International Fire Service Training Association. *Essentials of Firefighting*. Fire Protection Publications, Stillwater, OK, 7th edition.

[20] G. Corbett, editor. *Fire Engineering's Handbook for Firefighter I and II*. PennWell Corporation, 2019 edition.

[21] International Fire Service Training Association. *Structural Fire Fighting: Initial Response Strategy and Tactics*. Fire Protection Publications, Stillwater, OK, 2nd edition, 2017.

[22] Google Maps. Map Image - Wildwood Apartments, Marietta, GA, June 2019. https://www.google.com/maps/place/33%C2%B054'23.8%22N+84%C2%B028'11.0%22W/@33.9066697,-84.469895,18.26z/data=!4m5!3m4!1s0x0:0x0!8m2!3d33.9066004!4d-84.46971s.

[23] L.G. Blevins. Behavior of bare and aspirated thermocouples in compartment fires. In *National Heat Transfer Conference, 33rd Proceedings*, pages 15–17, 1999.

[24] W.M. Pitts, E. Braun, R. Peacock, H. Mitler, E. Johnson, P. Reneke, and L.G. Blevins. Temperature uncertainties for bare-bead and aspirated thermocouple measurements in fire environments. *ASTM Special Technical Publication*, 1427:3–15, 2003.

[25] S. Kerber and D. Madrzykowski. Evaluating Positive Pressure Ventilation In Large Structures: School Pressure and Fire Experiments. NISTTN 1498, National Institute of Standards and Technology, Gaithersburg, Maryland, 2008.

[26] R.A. Bryant. A comparison of gas velocity measurements in a full-scale enclosure fire. *Fire Safety Journal*, 44:793–800, 2009.

[27] M. Bundy, A. Hamins, E.L. Johnsson, S.C. Kim, G.H. Ko, and D.B. Lenhart. Measurements of Heat and Combustion Products in Reduced-Scale Ventilated-Limited Compartment Fires. NIST Technical Note 1483, National Institute of Standards and Technology, Gaithersburg, MD, 2007.

[28] A. Lock, M. Bundy, E.L. Johnsson, A. Hamins, G.H. Ko, C. Hwang, P. Fuss, and R. Harris. Experimental study of the effects of fuel type, fuel distribution, and vent size on full-scale underventilated compartment fires in an ISO 9705 room. NIST Technical Note 1603, National Institute of Standards and Technology, Gaithersburg, MD, 2008.

[29] J. Morehart, E. Zukoski, and T. Kubota. Characteristics of large diffusion flames burning in a vitiated atmosphere. In *In Proceedings of the Third International Symposium on Fire Safety Science*, pages 575–583, 1991.

[30] C. Beyler. *SFPE Handbook of Fire Protection Engineering*, chapter Flammability Limits of Premixed and Diffusion Flames. National Fire Protection Association, Quincy, Massachusetts, 5th edition, 2016.

[31] D.A. Purser. *SFPE Handbook of Fire Protection Engineering*, chapter Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. National Fire Protection Association, Quincy, Massachusetts, 5th edition, 2016.

[32] D.A. Purser. *Fire Toxicity*, chapter Asphyxiant components of fire effluents. Woodhead Publishing, Cambridge, UK, 2010.

[33] H. Utech. Status report on research programs for firefighters protective clothing. In *Proceedings of the Fire Department Instructor's Conference*, Indianapolis, Indiana, 1973.

[34] NFPA 1971. *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*. National Fire Protection Association, Quincy, Massachusetts, 2018.

[35] NFPA 1981. *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*. National Fire Protection Association, Quincy, Massachusetts, 2013.

[36] D. Madrzykowski. Fire Fighter Equipment Operational Environment: Evaluation of Thermal Conditions. UL Firefighter Safety Research Institute, Columbia, Maryland, August 2017.

[37] Center for Disease Control and Prevention (CDC), Atlanta, Georgia. *630–08–0: Carbon Monoxide*, 2014.

[38] S. Kerber, J. Regan, G. Horn, K. Fent, and D. Smith. Effect of Firefighting Intervention on Occupant Tenability during a Residential Fire. *Fire Technology*, 55:2289–2316, 2019.

[39] C. Weinschenk. Tactical Considerations Web Series: Ep. 1 - There Is No Substitute For Knowledge, May 2018. Accessed 12-12-2019 https://ulfirefightersafety.org/posts/tactical-considerations-web-series.html.

[40] NFPA 1901. *Standard for Automotive Fire Apparatus*. National Fire Protection Association, Quincy, Massachusetts, 2016.

[41] S. Kerber. Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes. *Fire Technology*, 48:865–891, October 2012.

[42] J. Tarley and T. Mezzanotte. Career Fire Fighter Dies After Falling Through the Floor Fighting a Structure Fire at a Local Residence – Ohio. NIOSH F2001-16, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2002.

[43] T. Merinar, J. Tarley, and S.T. Miles. Career Probationary Fire Fighter and Captain Die as a Result of Rapid Fire Progression in a Wind-Driven Residential Structure Fire – Texas. NIOSH F2009-11, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2010.

[44] M. Bowyer and M. Loflin. A Career Lieutenant and Fire Fighter/Paramedic Die in a Hillside Residential House Fire – California. NIOSH F2011-13, NIOSH Fire Fighter Fatality Investigation and Prevention Program, 2012.

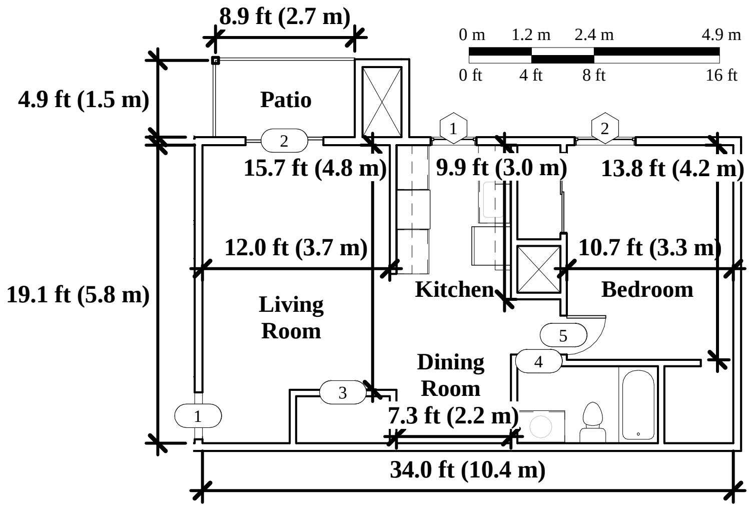
[45] S. Kerber, D. Madrzykowski, J. Dalton, and R. Backstrom. Improving Fire Safety by Understanding the Fire Performance of Engineered Floor Systems and Providing the Fire Service with Information for Tactical Decision Making. UL Firefighter Safety Research Institute, Northbrook, Illinois, March 2012.

[46] C. Weinschenk and R. Zevotek. Exploratory Analysis of the Impact of Ventilation on Strip Mall Fires. UL Firefighter Safety Research Institute, Columbia, Maryland, April 2020.

[47] NFPA 921. *Guide for Fire and Explosion Investigations*. National Fire Protection Association, Quincy, Massachusetts, 2017.

[48] NFPA 1670. *Standard on Operations and Training for Technical Search and Rescue Incidents*. National Fire Protection Association, Quincy, Massachusetts, 2017.

Appendix A Structure Dimensions



Unit Door Schedule				
Mark	Height	Width	Height	Width
1	6.7 ft	3.0 ft	2.0 m	0.9 m
2	6.7 ft	5.0 ft	2.0 m	1.5 m
3	6.6 ft	2.0 ft	2.0 m	0.6 m
4	6.6 ft	2.5 ft	2.0 m	0.8 m
5	6.6 ft	2.5 ft	2.0 m	0.8 m

Unit Window Schedule						
Mark	Sill Height	Height	Width	Sill Height	Height	Width
1	1.9 ft	4.8 ft	3.9 ft	0.6 m	1.5 m	1.2 m
1	1.9 ft	4.9 ft	3.0 ft	0.6 m	1.5 m	0.9 m
2	1.9 ft	4.9 ft	3.0 ft	0.6 m	1.5 m	0.9 m
2	1.9 ft	4.8 ft	3.9 ft	0.6 m	1.5 m	1.2 m

Unit Room Schedule				
Name	Area	Volume	Area	Volume
Bedroom	169.3 ft^2	1512.7 ft^3	15.7 m^2	42.8 m^3
Dining Room	91.6 ft^2	818.5 ft^3	8.5 m^2	23.2 m^3
Kitchen	60.5 ft^2	550.8 ft^3	5.6 m^2	15.6 m^3
Living Room	210.2 ft^2	1880.6 ft^3	19.5 m^2	53.3 m^3
Patio	45.0 ft^2	405.0 ft^3	4.2 m^2	11.5 m^3

Figure A.1: Apartment dimensions.

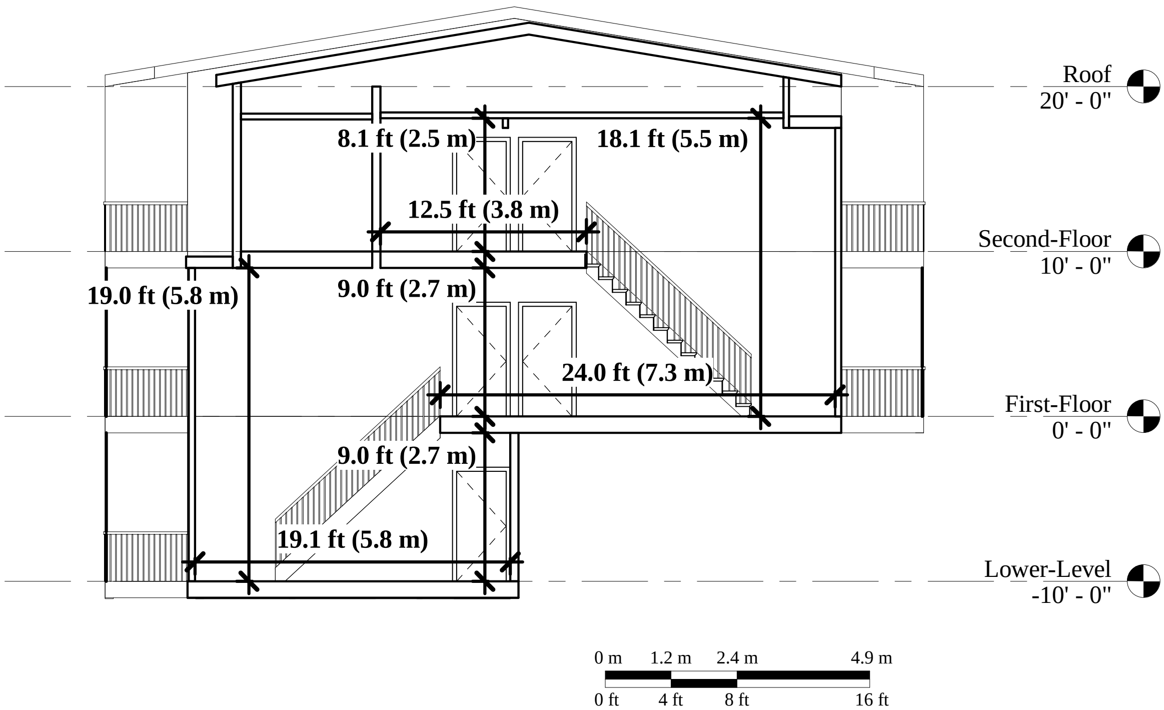


Figure A.2: Stairwell dimensions.

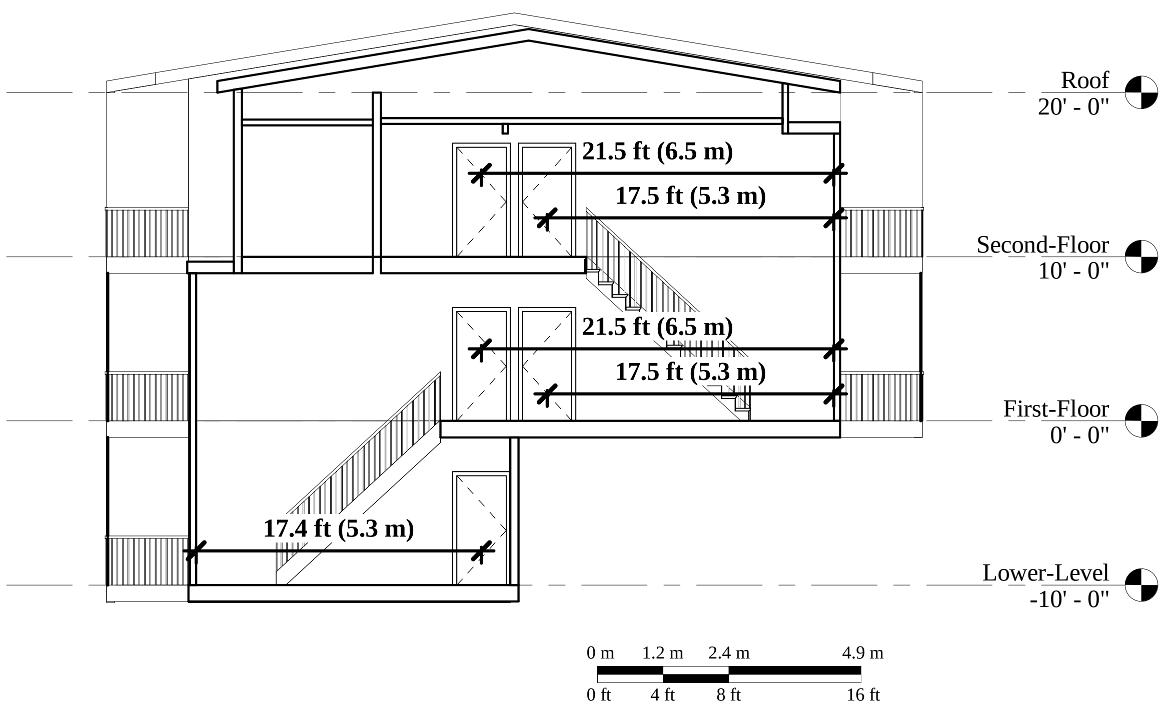


Figure A.3: Apartment door locations.

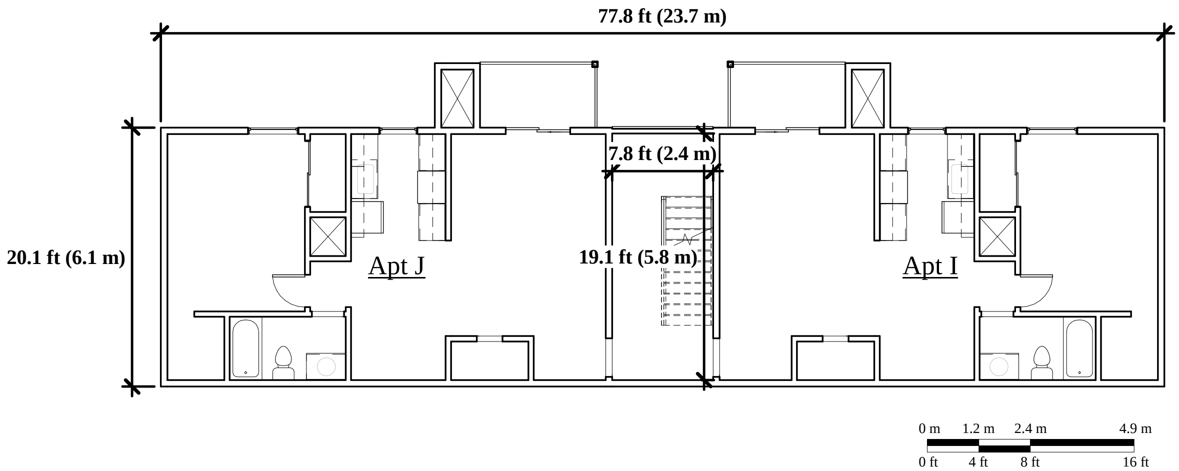
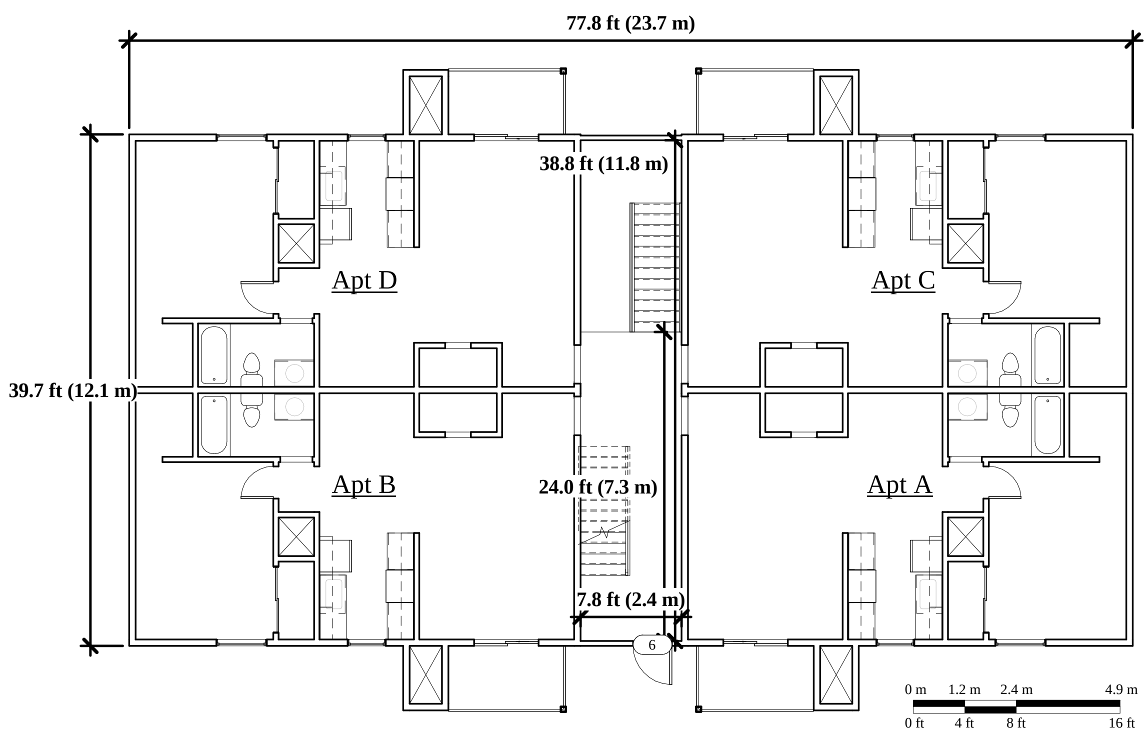


Figure A.4: Lower-level dimensions.



Complex Door Schedule				
Mark	Height	Width	Height	Width
6	6.7 ft	3.0 ft	2.0 m	0.9 m

Figure A.5: First-floor dimensions.

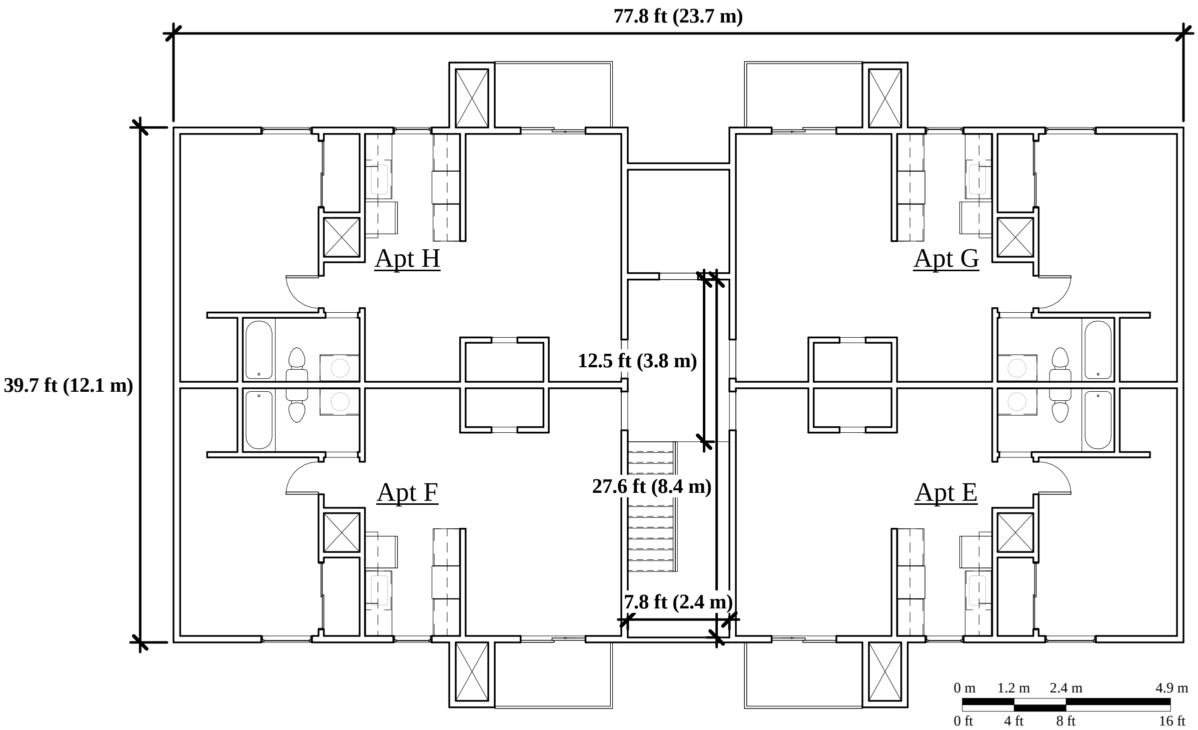


Figure A.6: Second-floor dimensions.

Appendix B Definitions

Bi-directional Vent: A building opening that simultaneously serves as both an inlet and an exhaust.

Building Sides: See Figure B.1 for an image depicting the Alpha (A), Bravo (B), Charlie (C), and Delta (D) sides of a structure.

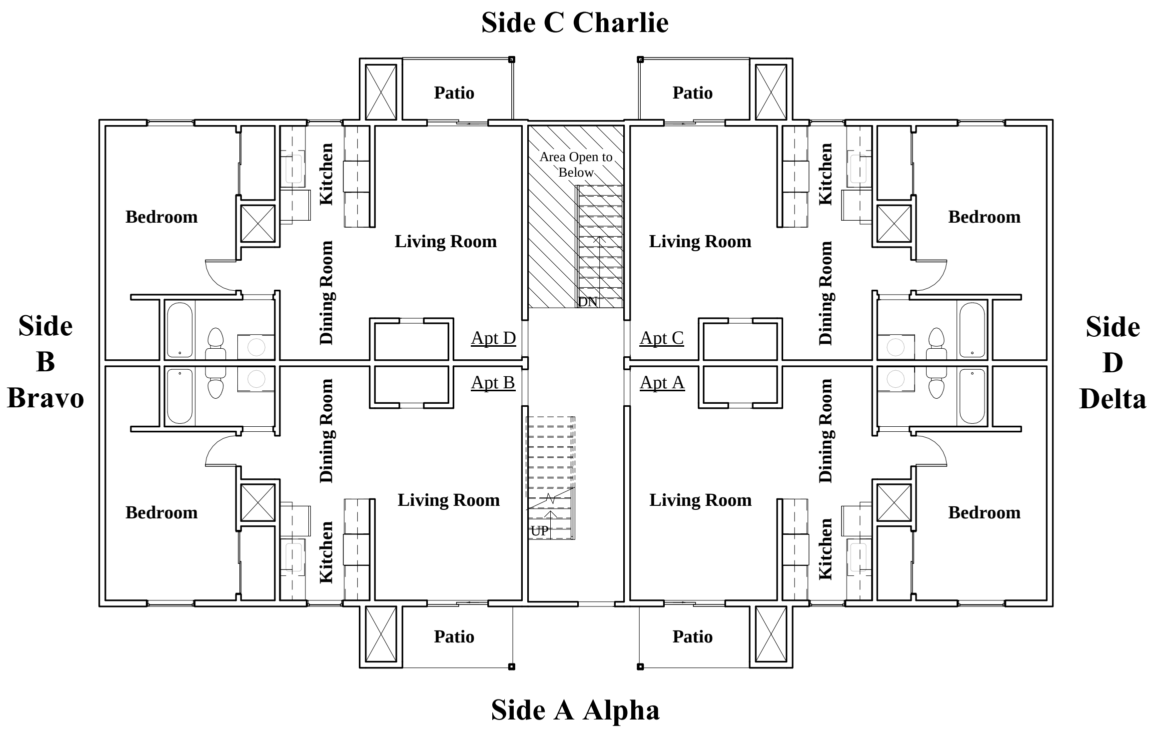


Figure B.1: Building side terminology.

Common Space: Areas within a given apartment that are connected with no ability to be isolated from each other. This includes the kitchen, dining room and living room.

Door Control: A firefighter positioned at a given doorway to control the opening by holding it in a semi-closed position while still allowing the passage of the hoseline. This is in attempts to limit the fresh air intake towards the fire and the exhaust of fire gases to other un-involved areas.

Enclosed Stairwell: For the purposes of this report, the previous breezeway stair located in the center of the structure was enclosed with walls in the front and rear, isolating it from the exterior. The stairwell had one exterior door, on the first floor, and all apartment doors opened into the stairwell.

Exterior Fire Control: Suppression operations performed on the exterior of the structure. This is not limited in time or direction of stream travel.

Fire Dynamics: The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior [47].

Floor Designations: See Figure B.2 for an image depicting the designations for each floor of the structure.

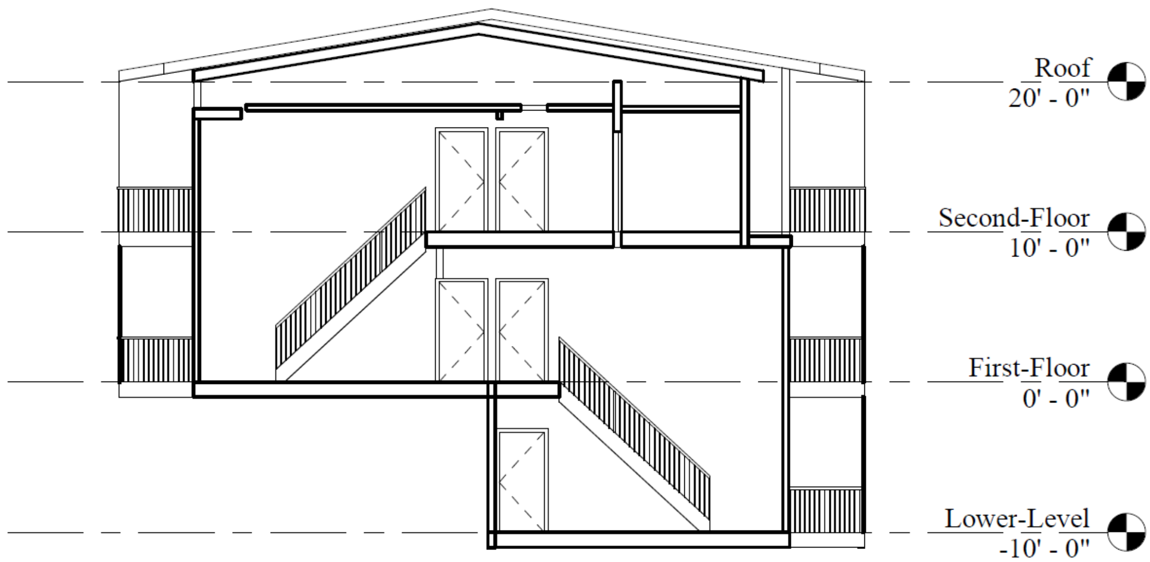


Figure B.2: Floor designations.

Flow Path: The route followed by smoke, air, heat, or flame toward or away from an opening; typically, a window, door, or other leakage point, due to differences in pressure.

Garden-Style Apartment: A structure that is typically two to three stories in height with the primary entrance to each apartment off of a common stairwell. This common stairwell can be open to the exterior (referred to as a breezeway) or enclosed.

Half-Bale: In the context of a suppression action, closing the nozzle to a point between fully open and fully closed with the intention of achieving a broken stream to improve the capability of the nozzle at wetting fuel surfaces.

Horizontal Ventilation: The act of making horizontal openings in the structure with the intent of removing smoke and heat while allowing the intake of fresh air to improve visibility and survivability. These horizontal openings are typically doors and windows.

Hydraulic Ventilation: Ventilation accomplished by using a spray stream to draw the smoke from a compartment through an exterior opening [19]. This is commonly performed utilizing a combination nozzle on a narrow fog pattern or a solid stream manipulated in an O pattern.

Immediately Dangerous to Life or Health (IDLH): Any condition that would pose an immediate or delayed threat to life, cause irreversible adverse health effects, or interfere with an individual's ability to escape unaided from a hazardous environment [48].

Interior Suppression: Suppression operations performed on the interior of the building.

Lintel: The top, horizontal member of a window frame. Also referred to as a window header.

Positive Pressure Attack (PPA): The use of positive pressure ventilation to control the flow of products of combustion, prior to fire control, with the intent of providing increased visibility and inability for firefighters and potential occupants while fire suppression efforts are underway [4].

Positive Pressure Ventilation (PPV): Method of ventilating a room or structure after fire control by mechanically blowing fresh air through an inlet opening into the space in sufficient volume to create a slight positive pressure within and thereby forcing the contaminated atmosphere out a given exit opening(s) [4].

Unidirectional vent: A building opening that serves as either an inlet or exhaust of a flow path.

Ventilation: Circulation of air in any space by natural wind or convection or by fans blowing air into or exhausting air out of a building; a firefighting operation of removing smoke and heat from the structure by opening windows and doors or making holes in the roof [47].